

F/G 9/1

DIAMOND TECHNOLOGY STUDY. (U)

JUN 79

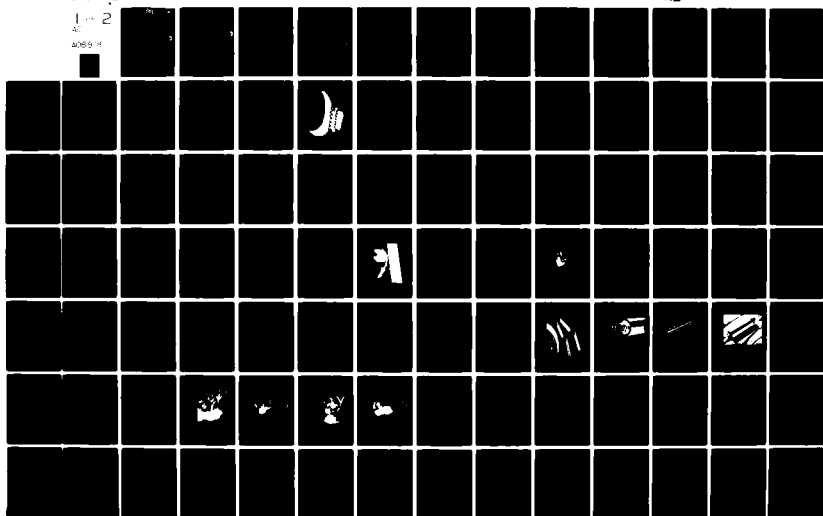
N00039-75-C-0451

NL

UNCLASSIFIED

1..2

4296



LEVEL



RAYTHEON COMPANY
Microwave and Power Tube Division
Waltham, Massachusetts 02154

ADA081928

9
6
FINAL REPORT, Jun 75 - Jan 79.
DIAMOND TECHNOLOGY STUDY.

DTIC
ELECTE
MAR 13 1980
S D

C

Prepared for

Department of the Navy
Naval Electronic Systems Command
Washington, D.C. 20360

15
Contract No. N00039-75-C-0451

14
PT-5413
11 June 1979
11

12 100

This document has been approved
for public release and sale; its
distribution is unlimited.



29831080 1 24 032

(1)

RAYTHEON COMPANY
Microwave and Power Tube Division
Waltham, Massachusetts 02154

FINAL REPORT
DIAMOND TECHNOLOGY STUDY

DTIC
ELECTE
MAR 13 1980
C

Prepared for
Department of the Navy
Naval Electronic Systems Command
Washington, D.C. 20360

Contract No. N00039-75-C-0451

PT-5413
11 June 1979

This document has been approved
for public release and sale; its
distribution is unlimited.

ii

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
1.0	INTRODUCTION	1
1.1	Purpose	2
1.2	Program	2
2.0	GENERAL TECHNICAL DISCUSSION	3
2.1	General Concepts	3
2.2	Diamond-Supported Helix Historical Review	7
2.3	Diamond to Metal Junctions	9
2.3.1	Bonding to Diamond	10
2.4	Calculation of Helix Temperature Rise	18
2.4.1	Package	20
2.4.2	PPM Pole	22
2.4.3	Shell	22
2.4.4	Interfaces (Shell to Diamonds and Helix to Diamonds)	24
2.4.5	Helix Supports	26
2.4.6	Helix Tape	26
2.4.7	Calculations	28
2.5	Diamond Properties and Procurement	29
2.5.1	Types of Diamonds and Properties	29
2.5.2	Fabrication of Diamond Parts	30
2.5.3	Alternative Materials	32
3.0	EXPERIMENTAL STUDY OF DIAMOND SUPPORTED HELIX	34
3.1	Phase I Comparison of Bonded versus Compression Helix Structures	34
3.1.1	Test Assembly Design	35
3.1.2	Compressed Tungsten Helix Assemblies	42
3.1.3	Bonded Copper Helix Assemblies	47
3.1.4	Discussion of Results	50
3.1.5	Conclusions	54
3.2	Phase 2 Diamond Supported Helix in a PPM Focusing Structure	54

TABLE OF CONTENTS (Cont'd)

<u>Section</u>	<u>Title</u>	<u>Page</u>
3.2.1	Helix Design-Electrical	55
3.2.2	Helix Design-Mechanical	55
3.2.3	Thermal Test Results - PPM Focused Assemblies	61
3.2.4	Conclusions	73
3.3	RF Properties	74
4.0	DELIVERIES	80
5.0	CONCLUSIONS AND RECOMMENDATIONS	81
APPENDIX A	Properties Of Diamond	
BIBLIOGRAPHY		

Accession For	
NTIS GRA&I	
DDC TAB	
Unannounced	
Justification	
By <i>on file</i>	
Distribution/	
Availability Codes	
Dist	Avail and/or special
<i>A</i>	

LIST OF ILLUSTRATIONS

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
1	Temperature Differences in a PPM Focused Helix TWT.	4
2	Thermal Conductivity vs Temperature	6
3	Helix Support Subassemblies in X and K-Band	11
4	Metal-Diamond-Metal Thermal Interface Test	16
5	Thermal Path-Helix to External Heat Sink	21
6	Coupling Impedance	37
7	Helix Velocity	38
8	Helix-Shell Assembly	39
9	K-Band Test Helix Parts	40
10	Helix Assembly (Thermal Test)	41
11	Thermal Test Assembly	43
12	Thermal Test Results	45
13	Thermal Test Results	49
14	Helix Temperature vs Power Dissipation	52
15	Temperature Profiles	53
16	Assembly Sequence	56
17	Diamond Helix Supports	57
18	Wire Wrapped Helix Assembly	58
19	Circuit Assembly Parts	59
20	Circuit Assembly	60
21	PPM Cell With Copper Rims Showing External Copper Cooling Blocks	62
22	PPM Cell Showing Imbedded Cooling Pipes	63
23	PPM Structure With Fluid Cooling	64
24	Thermal Test Assembly With External Heat Sink	65
25	Thermal Test Assembly With External Heat Sink	66
26	Thermal Test Assembly With Cross Flow Fluid Cooling Pipes	67
27	Thermal Test Assembly With Cross Flow Fluid Cooling Pipes	68

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
28	Thermal Test Assembly No. 2A	70
29	Thermal Test Assembly No. II-1.	71
30	Thermal Test Assembly No. II-2	72
31	Diamond Supported Helix Phase Velocity	75
32	Summary of Measured Helix Loss At Frequencies Above I-Band	76
33	Output Coupler Layout	78
34	Output Coupler Match	79
A-1	Thermal Conductivity vs Temperature	A-5
A-2	Linear Thermal Expansion	A-6

ABSTRACT

✓ A comprehensive study has been conducted into the use of diamond as a TWT helix support material to increase the average output power capability of broadband high frequency helix TWT's. A survey of the progress from the inception of diamond supported helix work in 1971, at Raytheon, to the present is presented. Methods for constructing diamond supported helices using compression, brazed, and diffusion bonded interfaces are described. The construction and test of experimental helix assemblies of all three types are described, and it is shown that a compression supported helix is most practical to design and build. Test results on compression-type copper plated tungsten helix assemblies are presented showing power dissipations of 1800 watts per inch for solenoid focused I-band helices and 500 watts per inch for PPM focused K-band helices. The emphasis was on development of practical engineering design technology.

A simple analysis procedure is described using thermal resistance methods for accurately calculating the temperature rise of a TWT helix for a given power dissipation. Correlation of calculated values with experimental results was good. This shows that the analysis method is accurate, and that the construction techniques used achieved the theoretical capability of the diamond supported helix. Detailed descriptions of the experimental results and methods are presented. ✕

Natural diamond is recommended as an excellent helix support material when higher average output power is required than can be achieved by use of conventional dielectrics. The results of this study indicate that average output power of over 500 watts solenoid focused and 250 watts PPM focused should be practical in K-band. By extrapolation we can predict that 100 watts average output should be practical at 40 GHz in a PPM focused helix TWT and 200 watts in a solenoid focused tube.

This is the final report for contract number N00039-75-C-0451; and it covers work done during the period from June 1975 through January 1979. Conclusions and recommendations for further work also are given.

vii

1.0 INTRODUCTION

Considerable engineering effort in recent years has been devoted to the development of methods for increasing the average power capability of the unifilar helix traveling-wave tube. The motivation has been the need for broadband TWT's capable of high average power. Since the unifilar helix is the one TWT circuit capable of broadband operation with good efficiency, methods to increase its power dissipation capability are of great interest. The work of this program has been devoted to development of the technology for diamond supported helix TWT's with high average power capability.

Increasing the average output power capability of a helix TWT must be accomplished by improving the thermal conduction from the helix to the outer shell. Hence, ever since the invention of the TWT, the average output power from helix TWT's has been tied closely to materials technology. State-of-the-art power levels increased from a few watts to a hundred watts when high purity alumina ceramic became available as a replacement for glass as support material. Another increment to several hundred watts, in I-band, was made when beryllia and boron nitride, with higher thermal conductivity, became available. Diamond has the highest thermal conductivity of any material known in the operating temperature range of TWT circuits, is an excellent dielectric, and is the next logical step in this progression.

Raytheon Company has made considerable progress toward utilizing diamonds in TWT's on U.S. Navy sponsored TWT development programs. These development programs have been directed toward furthering the state-of-the-art in diverse areas of TWT performance, including improved average power. The portion of development effort allotted to developing diamond-supported circuits has been restricted by the work statement for each particular program to the minimum needed to achieve the required performance in that TWT. Thus, a general study of the various methods for constructing diamond supported helices had not been undertaken prior to this program. However, it had become

apparent that major technique improvements could be made so that, in any particular application, the proper design approach could be used to achieve high average power in helix TWT's. In a sense, the past work on the diamond-supported helix, even though fragmented among several individual programs, has helped to define more clearly the basic technology problems which must be solved to enable the full utilization of diamonds in microwave tubes.

In general, an experimental approach to this technology study was adopted. A thorough literature search and discussion with appropriate experts furnished the necessary background of knowledge. Since the diamond supported helix structure was originated several years ago at Raytheon a review of the history of work here was conducted to further aid in defining the necessary work. Backup on the theory of bonding to diamonds and/or other techniques was furnished by Raytheon's Materials and Techniques Laboratory.

1.1 Purpose

The purpose of this program has been to develop, refine, and evaluate the processes necessary for utilization of diamond insulators as helix supports to obtain higher average output power in broadband TWT's at frequencies of I-band and above. The statement of work as amended defined this in more specific detail.

1.2 Program

This program was conducted in two phases. In the first phase, the various methods for construction of a diamond supported helix were compared and key experimental assemblies were built and evaluated. In the second phase, as redefined in a modification of the contract, the specific subject of heat transfer from a diamond supported helix out through a PPM focusing structure was studied by theoretical and experimental work.

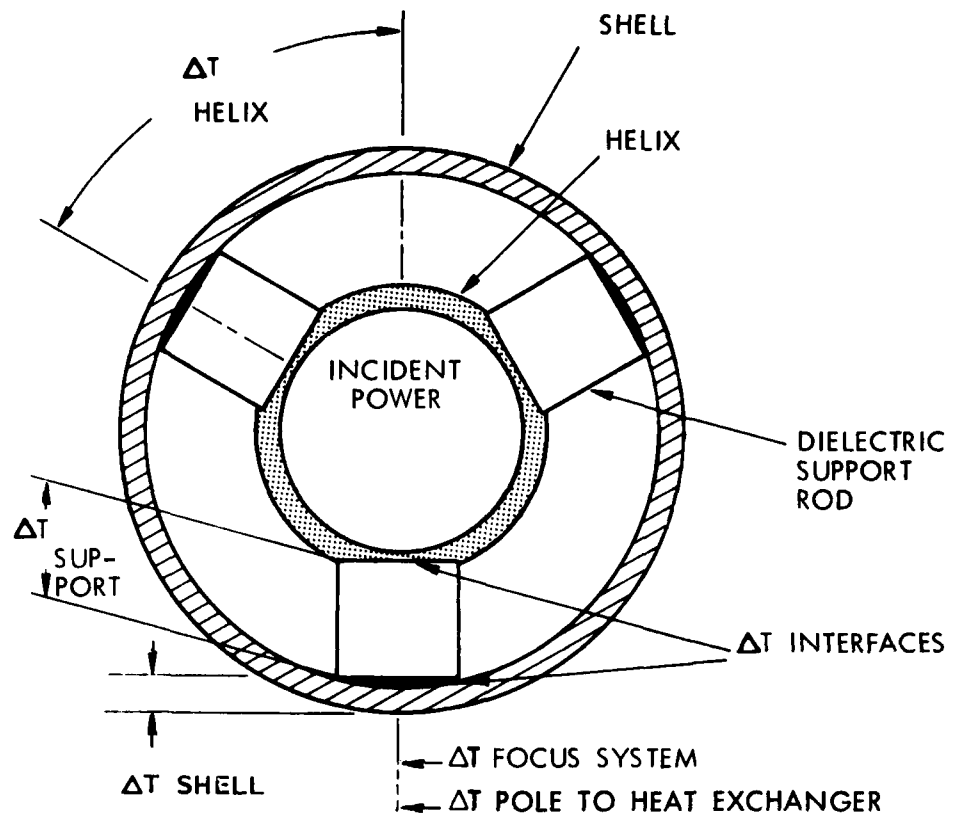
2.0 GENERAL TECHNICAL DISCUSSION

2.1 General Concepts

The unifilar helix supported by dielectric rods or posts within the vacuum envelope has the broadest bandwidth of any TWT interaction circuit. During TWT operation, heat is dissipated in the helix interaction circuit due to rf loss and from the interception of a small percentage of the beam electrons. Heating of the interaction circuit is one of the major factors limiting the power level at which broadband TWT's can be operated.

Heat appearing in the helix as a result of rf dissipation and beam interception must be conducted out through the dielectric supports and the surrounding mechanical and focusing structure for the TWT, as shown schematically in Figure 1. The temperature of the helix rises in proportion to the average power of the TWT, and, in general, it is accepted that a safe operating helix temperature upper limit is about 400 to 450°C.

To limit the temperature rise in the helix, a high conductance path must be provided to the heat exchanger. The dielectric support rod and the interfaces between it and the metal parts of the tube are the highest impedance elements in this path. In TWT's operating at state-of-the-art power levels, dielectric supports are selected which have high thermal conductivity, and care is exercised to minimize the temperature drop across the interfaces. The state-of-the-art in power amplification has been closely related to the types of materials which are available for use as support insulators, and the methods for making good thermal interfaces between metal parts and the dielectric supports. Thus, brazing technology, metalizing methods, and compression fitting methods all have affected the power capability of helix structures.



$$\Delta T \text{ HELIX TO SHELL} = \Delta T \text{ HELIX} + \Delta T \text{ INTERFACES} + \Delta T \text{ SUPPORT}$$

941502

Figure 1. Temperature Differences in a PPM Focused Helix TWT.

In the early days of TWT's, the primary support materials were quartz and glass. These materials have such low thermal conductivity that the operation of TWT's was limited to a few watts of average power. High purity alumina ceramics and sapphire, which have thermal conductivity several times that of glass and quartz, made it possible to increase the average operating power to one hundred watts in I-band. In the later 1960's, beryllium oxide and boron nitride ceramics, having a thermal conductivity four or five times that of alumina ceramics, became available. The use of these higher conductivity materials made possible the increase in average operating power of broadband TWT's to three to four hundred watts in I-band and one to two hundred watt levels in J-band. From Figure 2 it is evident that natural diamond has a thermal conductivity eight or ten times higher than beryllium oxide or boron nitride. Use of natural diamonds for circuit supports will lower the temperature drop across the circuit supports making it possible to operate at higher power levels without increasing the helix temperature. Likewise, for operation at any given power level, it will reduce the helix operating temperature and thus improve the reliability of the TWT.

It is possible to incorporate diamond supports into established designs because the dielectric constant is very little different from that of beryllium oxide, or anisotropic boron nitride, (Boralloy), which are the most widely used materials in high power broadband TWT's. The hardness and surface finish of diamond are superior to those of other dielectric supports, hence will provide better resistance to voltage breakdown at high peak levels. Expansion coefficient of diamond is lower than the other materials listed above. The similarities in the physical and microwave properties of the diamonds make it possible to incorporate them into proven designs with few dimensional changes.

However, the technology required to utilize diamond helix supports, while similar to ordinary TWT technology, required some development. This is because of the fact that diamond is a material whose properties are somewhat different from ordinary dielectrics. It is the hardest material known, so that

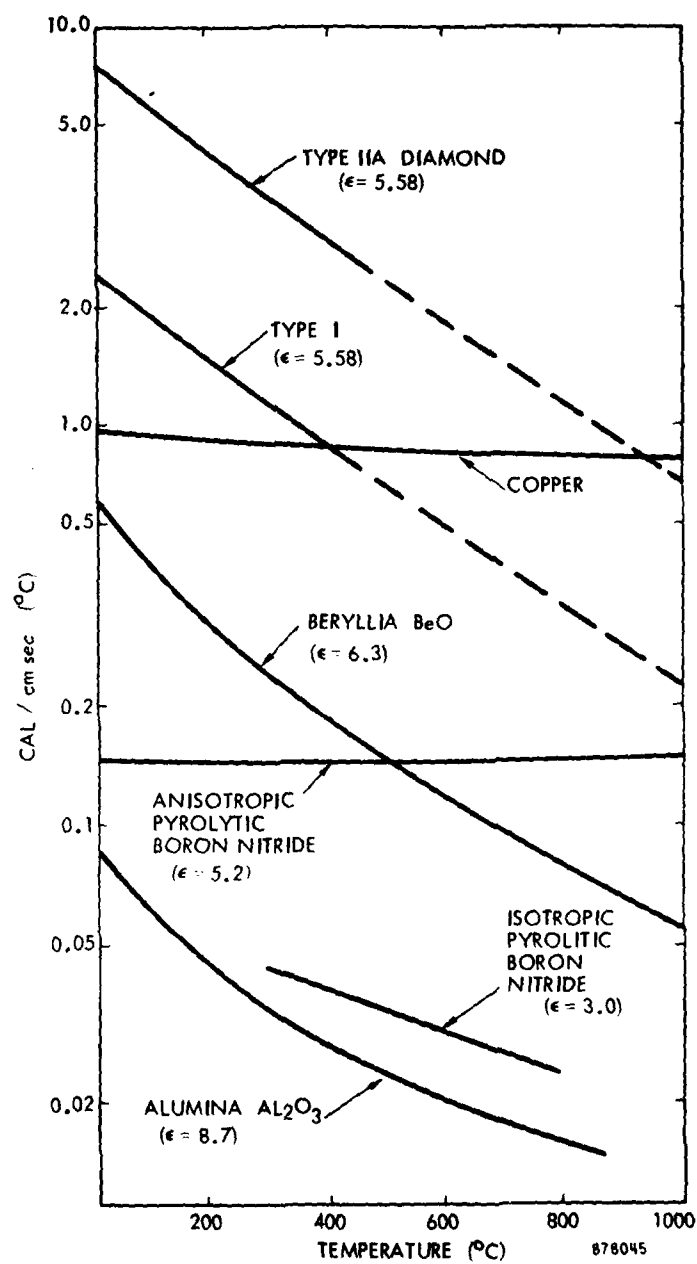


Figure 2. Thermal Conductivity vs Temperature.

special techniques are required to shape it and not all shapes are feasible. There are maximum size limitations set by the availability of natural diamonds (synthetic diamonds have not as yet been made which have good enough dielectric and thermal properties). Brazing and/or bonding of metal to diamond requires techniques similar to, but different from in important ways, the usual ceramic to metal sealing techniques. Thus, the use of diamond helix supports in practical TWT's has taken an appreciable amount of technology development work to date. The basic technology now has been developed to the point where practical TWT's using diamond supported helices can be designed and built. This report describes the various methods for making diamond supported helices and compares the relative advantages of each. A brief historical review of diamond-supported helix technology prior to this program is presented next, followed by a summary of the state of the art.

2.2 Diamond-Supported Helix Historical Review

A brief summary of the history of the diamond-supported helix TWT structure is presented here to help explain the reasons for the work planned for this program. Shortly after the publication of a paper⁽¹⁾ describing techniques developed by Bell Telephone Laboratories for bonding high power microwave diodes to diamond heat sinks, an investigation of the possible use of diamond as a TWT helix support was started here at Raytheon⁽²⁾. This work was only carried far enough to verify that we could gold-braze copper to diamond with a good thermal junction at the interface and that diamond did indeed have desirable dielectric properties. The results, as they would apply to a high power Ku-band TWT design, were described in the final report of that program⁽³⁾.

After the completion of the Raytheon IDA-523 program, attempts were made to incorporate diamonds into two traveling-wave tubes which already were in development for the U.S. Navy. In the first case, a 2-kilowatt cw X-band TWT had been in development for several years and many failures due to

helix overheating and burnout had occurred. A design change was initiated to convert this tube from a CVD BN-supported helix to a copper helix brazed to diamond supports. One tube was built using metalized diamonds, silver brazed to the helix; but, there was excessive rf loss due to evaporation of a thin layer of silver onto the diamonds, during the vacuum brazing procedure. The gain, therefore, was too low to allow a full evaluation of the power capability of the tube. Another helix assembly was built using gold brazing solder, and just before the funding of the program ran out, this helix was tested at very high cw power level in a resonant ring driven by a high power I-band cw klystron. The results showed that the helix could easily handle more than 2500 watts of cw I-band rf power. In building this helix many delays were encountered due to problems associated with metalizing and brazing to the diamond-helix supports. Patch-work type remedies were devised just to get this one helix assembly constructed; but, the problems were by no means adequately solved.

In the second case a program was underway for the U.S. Navy to establish the feasibility of designing and building a helix TWT capable of extremely high peak and average power output at I-band. The first goal of this program was to demonstrate the achievement of very high peak power across nearly an octave bandwidth at I-band, and a secondary goal was to demonstrate high average power capability. A diamond-supported helix design was chosen to give the highest possible average power capability. Achievement of the very high peak power (approximately 5 times the existing state-of-the-art) required the invention of a new design approach (fast wave velocity steps) and the primary emphasis was placed on this aspect of the design. At the end of the program a tube was built using a diamond-supported helix, but beam focusing problems, which were not corrected, precluded any attempt to operate at other than low duty cycle. Thus, no demonstration of the high average power capability of a diamond-supported helix was achieved in this program even though an actual operating TWT was built and tested at low duty cycle and extremely high peak output power.

The preceding descriptions show that the initial approach to using diamond helix supports was to immediately attempt to incorporate them into TWT designs already in development on the assumption that conventional brazing techniques would be usable. In each case problems arose which could not be solved within the constraints of time and cost imposed by the program plans. This shows that the use of diamond as a TWT helix support had not been the subject of a really thorough investigation. Instead, attempts to use diamond helix supports had been done only on development programs in which that aspect was secondary to the primary objectives of the programs. Clearly, there was a need to upgrade the technology involved in using diamonds in microwave tubes.

Raytheon carried out a technology study program in 1974 and 1975 to solve the basic technology problems involved in using diamond helix supports in TWT's. Processes for metalizing and brazing to diamonds, and for direct active metal alloy diffusion bonding to diamonds were developed. Also, it was demonstrated that a compression joint of diamond to metal will have excellent thermal conductivity (equal to the best brazed joint) if properly done. However, it was recognized that much experimental work still needed doing to establish and compare the reliability of these processes; and that was one of the major reasons for the initiation of this program to build and evaluate test assemblies.

2.3 Diamond to Metal Junctions

In order to successfully use diamonds as helix supports in a TWT, it is necessary to have a good method for making the junction of the diamonds to the metal helix and outer shell. These junctions must have excellent thermal conductivity and must have enough mechanical integrity to maintain the same characteristics through TWT processing and use. In addition, the method for making the junction must be controllable so that consistently good assemblies can be fabricated. Two basic types of junctions can be used between the metal helix and the dielectric supports; namely, junctions in which there is a braze or a bond of the metal to

the insulator, and junctions in which the metal is held against the insulator by mechanical force great enough to give a good thermal contact. In each of these two families there are several different types of structures and the most interesting ones are described below.

2.3.1 Bonding to Diamond

Bonding of the metal to the diamond can be done by brazing with conventional solders to metalized diamonds, by using active metal alloy solders, or by active metal diffusion bonding.

1. Brazing to Diamond

The use of metalization of diamond to aid in bonding of semiconductor devices to diamond heat sinks was originally developed at Bell Laboratories. The metalizing system reported by Schorr (600 Å Ti, 2000 Å Pt, followed by 10,000 Å Au) was used here at Raytheon for the first experimental brazing of diamond to copper using gold as the solder. As mentioned earlier, several TWT helix assemblies were brazed using metalizing; but there were problems with adherence in some metalizing batches. Here in MTO, improvements in the metalizing process have been made so that a higher yield of good batches is now being obtained using a Mo-Cu system. Brazed structures have excellent thermal properties, as has been demonstrated. Subassemblies consisting of diamond cubes bonded to back-up strips have been made for use in diamond-supported helix assemblies. Typical subassemblies are shown in Figure 3. These units can then be installed in a helix assembly in much the same way as an ordinary dielectric rod support which has been notched between the helix turns.

However, one major disadvantage of the use of metalized diamonds brazed in place to form helix supports is the necessity for cleaning the metalizing off the exposed surfaces so that the diamonds can function as helix support insulators. Cleaning the metalizing off of selected surfaces of the diamonds

PT-5413

75-74566

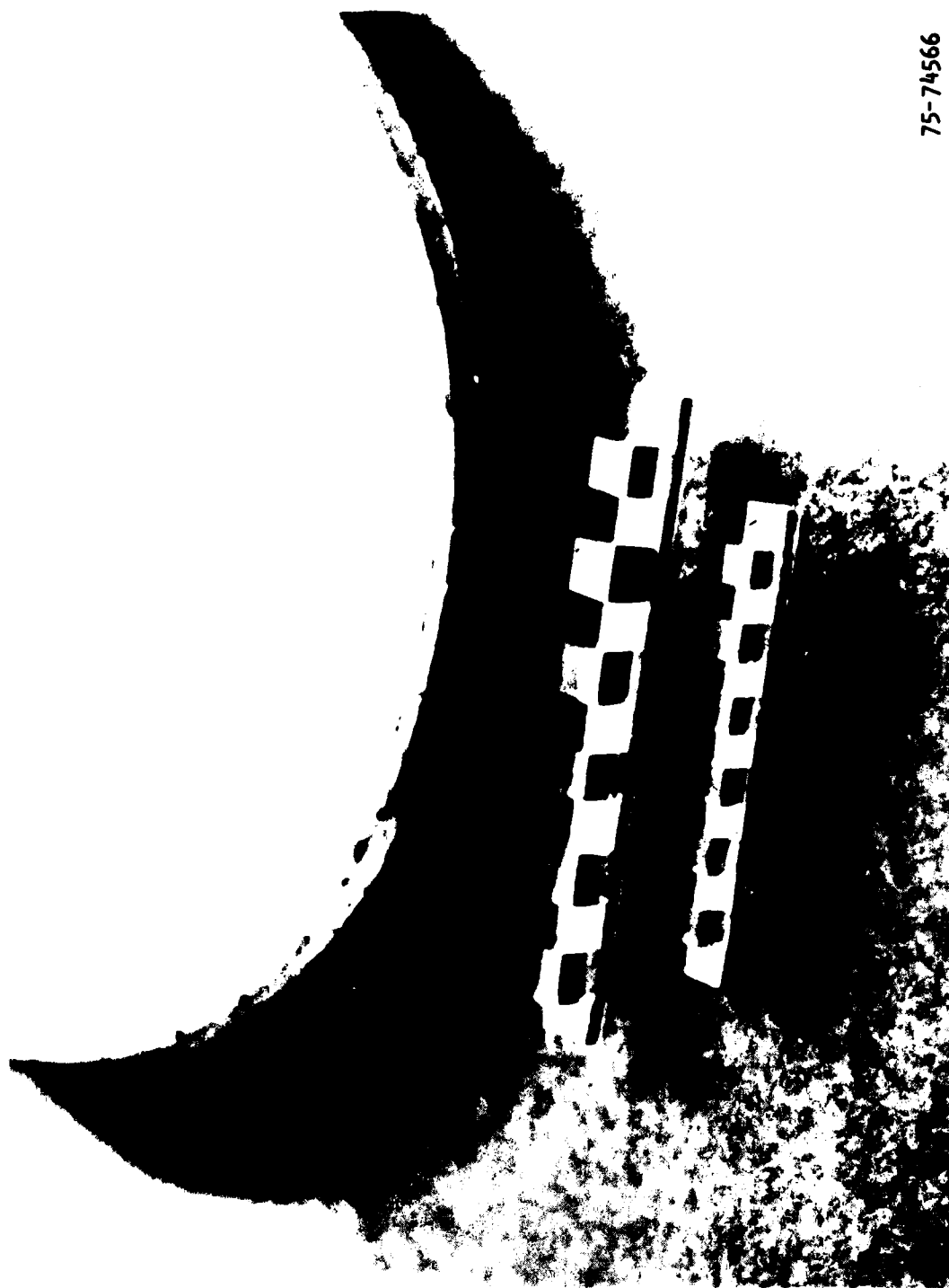


Figure 3. Helix Support Subassemblies in X and K-Band.

has been tried both by chemical etching and by mechanical abrasion either before or after brazing them in place. The problem is to remove all of the metalizing in the correct area without damaging it in the brazing area. This typically has been done by using a pencil sandblaster in a costly, tedious, hand operation. Alternatively, the diamonds could be metalized on only the surfaces to which brazing is intended with the other surfaces kept clean by masking. Since the metalizing is done by a sputtering process, the mask must be in close contact with the diamond to avoid deposition under the mask, and must be made out of a material which will not contaminate the sputtering process. The small size of the diamonds (typically 1/2 millimeter cubes) means that a masking fixture must be made to very tight tolerances and have quite small dimensions.

Since the major problem associated with using metalized diamonds is that of making certain that the correct surfaces are free of metalizing, it was decided to use other methods which bond directly to an unmetalized diamond.

2. Active Metal Alloy Brazing

The use of active metal alloy solders for brazing directly to ceramics has been known for years. Seal⁽⁴⁾, in a survey paper, describes several alloys which have been used to braze to diamond (e.g.: Cu-Ag-Ti, Au-Ti, Au-Al-Ta) and discusses the criteria for a molten metal to wet and bond to diamond surface. He concludes that alloys containing transition metals, such as titanium, zirconium, vanadium, niobium, tantalum, will be most likely to bond to diamond because they react to form carbides and also have the ability to remove chemisorbed oxygen from the diamond surface. Therefore, it seems reasonable to expect that molten active metal-copper alloy might wet diamond and make a good braze to diamond.

In fact, experiments several years ago at Raytheon showed that diamonds could be brazed to tungsten using active metal-copper alloys by heating in vacuum to a temperature slightly above the melting point of the alloy.

Strong joints were obtained but the expansion differential tended to crack the tungsten at times. However, the major disadvantage was that the molten alloy wets the diamond and flows over the surfaces where clean dielectric is desired. Accordingly, diffusion bonding was chosen as being more practical.

3. Active Metal Alloy Diffusion Bonding

An alloy containing an active carbide forming element will form a bond to diamond under the proper conditions of contact pressure and temperature. The use of such a bonding process in which no wetting and flowing occurs is ideal for making diamond-supported helix assemblies because the surfaces of the diamonds which are exposed to the rf fields remain clean. A process for bonding diamonds to the copper alloy containing a small percentage of zirconium was developed at Raytheon several years ago for making subassemblies consisting of a row of diamond cubes bonded to the metal support strip for use in diamond supported helix assemblies ⁽⁵⁾.

The diamond to zirconium-copper bonding process appears to be very useful. Many helix support subassemblies have been made using this process with excellent results. These subassemblies consist of six cubical diamonds bonded to an Amzirc* ribbon (0.010 in. x 0.030 in) spaced so as to align with the turns of a helix in experimental helix assemblies. Figure 3 shows a photograph of two different size typical diamond subassemblies. The diamond to metal bonds have all been extremely good for thermal conduction as measured in helix assembly tests described later in this report. The mechanical strength of the bond has been tested on several subassemblies by pulling them apart. The failures always occur either by the metal tearing apart and leaving a layer on the diamond or by the diamond cleaving or cracking apart. Due to the extremely small size of these units it has not been possible to make a quantitative measurement of the full strength of the bond, but it is certain that the bond is at least as strong as the solid material. Diamond support subassemblies of this type are used in the low-band millimeter wave TWT developed under Navy Contract number N00014-74-C-0026.

* Trade name for AMAX, Inc.

Since the thermal conductivity of the zirconium copper alloy is about 95% that of pure copper (in the full solution annealed condition after aging at 500°C), a further application of this process was proposed in which the helix tape was made of the alloy and then bonded to the diamond supports. Such a structure should be equivalent in thermal dissipation capability to a copper helix brazed to metalized diamonds without the problems of confining the metal to the specific areas of contact. Accordingly, this active metal alloy bonding process was chosen as one of the methods for constructing diamond-supported helix assemblies to be tested in this program. The results were mixed, as described later.

It should also be noted that a fundamental requirement for this process is a high temperature high vacuum furnace capable of maintaining a pressure below 5×10^{-7} Torr at a temperature of 1000°C. Such a furnace was purchased by Raytheon in 1975 and has been used since then. Problems were encountered in the process of learning how to use this furnace which caused delays at times, but these have been solved so that the process of bonding diamonds to metal now is routine.

4. Pressure Interface

A common assembly method for a helix supported by beryllia or boron nitride rods is to have the helix held in compression within an outer shell assembly. Typically the helix is wound from either tungsten or molybdenum and the pressure of the outer shell on the rods holds them firmly against the helix to give the necessary conduction of heat outward. The thermal joints which are obtained typically are not as good as a brazed joint when ordinary ceramics are used.

In the case of diamond to metal interfaces, excellent thermal conduction equal to the best brazed joint can be obtained if the correct process is followed. A recent paper discussed the subject of metal interfaces which are held together by pressure rather than by a bond ⁽⁶⁾. This paper describes work done at the Adamant Division De Beers Diamond Research Laboratory, Johannesburg.

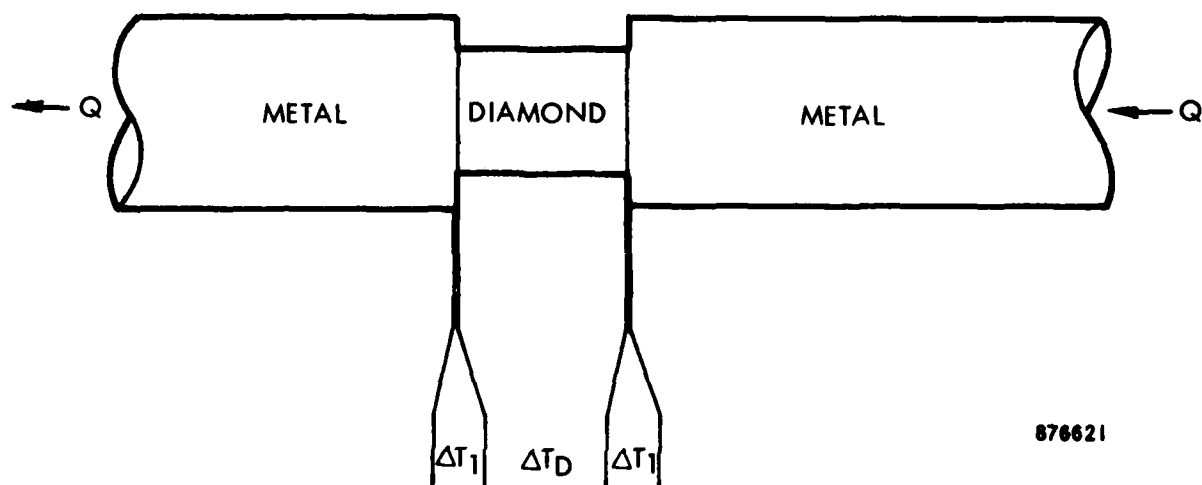
South Africa. A series of experimental measurements of thermal conduction through a diamond cube when clamped between two pieces of metal were made. Various metals were used and variations in contact pressure, surface cleanliness, and coatings on the diamond were investigated. They concluded that excellent thermal contacts can be obtained by pressure without a braze, between metal and diamond if certain criteria are met: (summarizing their results)

1. Contact pressure not less than 20 kg/cm²
2. Use of a soft metal, such as gold, at the interface reduces the interface resistance. (We believe soft copper does as well).
3. Metal oxides must be eliminated.
4. Polycrystalline metal deposits on the diamond do not reduce the metal-diamond interface resistance.
5. Epitaxial nickel and titanium coatings on the diamond reduce the interface resistance.

Examining the experimental results they reported, it was apparent that a joint of clean copper to diamond should give a satisfactory thermal joint for our purposes. In the paper all thermal resistances are quoted in arbitrary "cal units" including the thermal resistance of the diamond. It is possible to convert from these units to more standardized units as follows: Consider the test structure they used as shown in Figure 4. By simple arithmetic from their test results, the diamond to metal interface thermal resistivity in standard units is found to be:

$$\rho = 0.00888 \text{ cm}^2\text{ }^\circ\text{C watt}^{-1}$$

This is much better than the value of 0.0456 which was measured on copper to beryllia interfaces some years ago. Since the basic scientific measurements of the thermal interface had been made and published it was not necessary to repeat the measurements here. Instead the emphasis was placed upon the practical engineering aspects of constructing the helix assembly to obtain the desired contact conditions at the interface between the diamonds and the helix.



876621

Figure 4. Metal-Diamond-Metal Thermal Interface Test.

Tests at Raytheon, a year before this program started, on copper plated tungsten helices held in compression by diamond supports had shown temperature rise of 340°C at 1040 watts per inch dissipation. Calculations from those test results give a thermal contact resistivity of $0.009 \text{ cm}^2 \text{ } ^\circ\text{C watt}^{-1}$, which is in excellent agreement with the results of Caveney et al.

Therefore, the compression diamond-supported helix structure has been used in the low-band millimeter wave TWT, and this structure was chosen for further investigation in this program. The excellent thermal interface which is obtained by compression of copper to diamond most probably results from several factors:

1. The extreme hardness of diamond so that a soft metal copper will, under pressure, flow plastically to make good large area contact.
2. The high polish finish which is obtainable on diamond so that there is little surface roughness to interrupt the contact area.
3. The extremely high thermal conductivities of both copper and diamond.
4. Both surfaces clean and free of oxide layers.

It has been found relatively easy with ordinary vacuum tube processing techniques to meet the requirements for cleanliness and pressure at the interface.

In complete agreement with these results are results reported to us by Dr. Michael Seal of D. Drukker & Son when he visited Raytheon in November 1974. In experiments in their Test and Development Laboratory, they found that a pressure interface between a metalized diamond and gold with an indium layer between has excellent thermal properties.

It is doubtful that the indium layer would be of use to us in TWT's; but it confirms our belief that a good thermal interface can be obtained between soft metal and diamond with pressure to hold them together.

The conclusion is that, if the correct compression, material hardness, mechanical fit, and material cleanliness are maintained, a compression fit diamond supported helix can have as good a thermal interface between the metal and the diamond as a brazed structure.

2.4 Calculation of Helix Temperature Rise

There are two sources of heat in a TWT helix, the rf power and the electron beam. The rf power flowing on the helix causes ohmic heating proportional to the skin effect resistance of the helix. Imperfect focusing of the electron beam results in a small fraction of the electrons hitting the helix and dissipating their kinetic energy. The first effect (1) is directly proportional to the output power and is of serious consequence only near the output end of the helix. The second effect consists of two parts, a dc interception power (2a) with no rf drive and an additional interception power (2b) when rf modulation on the beam causes beam expansion. In addition, if the depressed collector is poorly designed, there may be backstreaming electrons from the collector which hit (2c) the output end of the helix. It is assumed that proper design eliminates this heating effect.

Effect (1) causes heating which is predictable and can only be reduced to a basic ground level by minimizing the helix loss; this basic level of heating must be accepted in the design. Heating due to effect (2a) is usually spread out over a goodly portion of the input section of the helix where there is no other power dissipation. Heating due to effect (2b) occurs in the same region where rf heating (1) occurs so that the output end of the helix must dissipate the most heat. Thus, the sum of these two heating effects must be used in calculating the rf output power capability of a helix TWT.

The heat generated in the helix of a TWT can only leave by two means, conduction through the supports, and radiation.* Since the normal operation temperature of a helix must be kept below approximately 450°C, the heat loss by radiation is negligible compared to conduction heat flow and can be neglected. The temperature to which the helix rises is that at which the heat flow out (which is proportional to temperature difference) just balances the heat generated in the helix. The calculation of this can be accomplished with quite good accuracy by use of a developed one-dimensional thermal conduction model and using the one-dimensional heat flow Fourier equation (which becomes the Poisson equation for a steady state time invariant case)

$$\text{i.e.} \quad \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{k} = 0$$

which becomes in a one-dimensional linear case:

$$\frac{d^2 T}{dx^2} + \frac{q}{k} = 0$$

the solution to which is called the Fourier law:

$$q = -kA \frac{dT}{dx}$$

or

$$q = \frac{kA}{x} (T_1 - T_2)$$

Similarly, in a cylindrical system with heat flowing only in the radial direction, and no temperature variation in either the θ or z directions, the Fourier law becomes:

$$q = -2\pi krL \frac{dT}{dr}$$

or

$$q = \frac{2\pi kL(T_1 - T_2)}{\ln \frac{r_2}{r_1}}$$

* The type of helix which is cooled by direct circulation of a fluid through a hollow helix is not considered here. It has been completely described in other publications and is not useful above about 10 GHz.

It is convenient to model the helix supported by thermally conducting dielectric rods inside of a PPM focusing system as a series of "thermal resistances" for each of which the thermal resistance can be calculated by use of the appropriate one-dimensional Fourier equation. This method is described in detail by Kraus.⁽⁷⁾ With reasonable care in choice of the thermal resistance boundaries this then reduces the thermal calculations to a standard electrical resistance problem. This is far more convenient and much simpler than attempting to carry out a complete three-dimensional solution of Poisson's equation with a computer program using either a Liebman net relaxation technique or a finite element method. In this method it is easy to obtain quite good accuracy by performing the calculations iteratively to include temperature variation of the thermal conductivity of the material.

Figure 1 defines the temperature differences in a PPM focused TWT helix. The thermal resistances for the various elements of this configuration then can be defined as follows (referring to Figure 5):

In a linear (rectangular) coordinate system:

$$q = \frac{kA}{L} (T_1 - T_2)$$

so that the thermal resistance is:

$$R_T = \frac{L}{kA}$$

where: the heat flow (q) is analogous to electrical current and the temperature difference ($T_1 - T_2$) is analogous to electrical voltage.

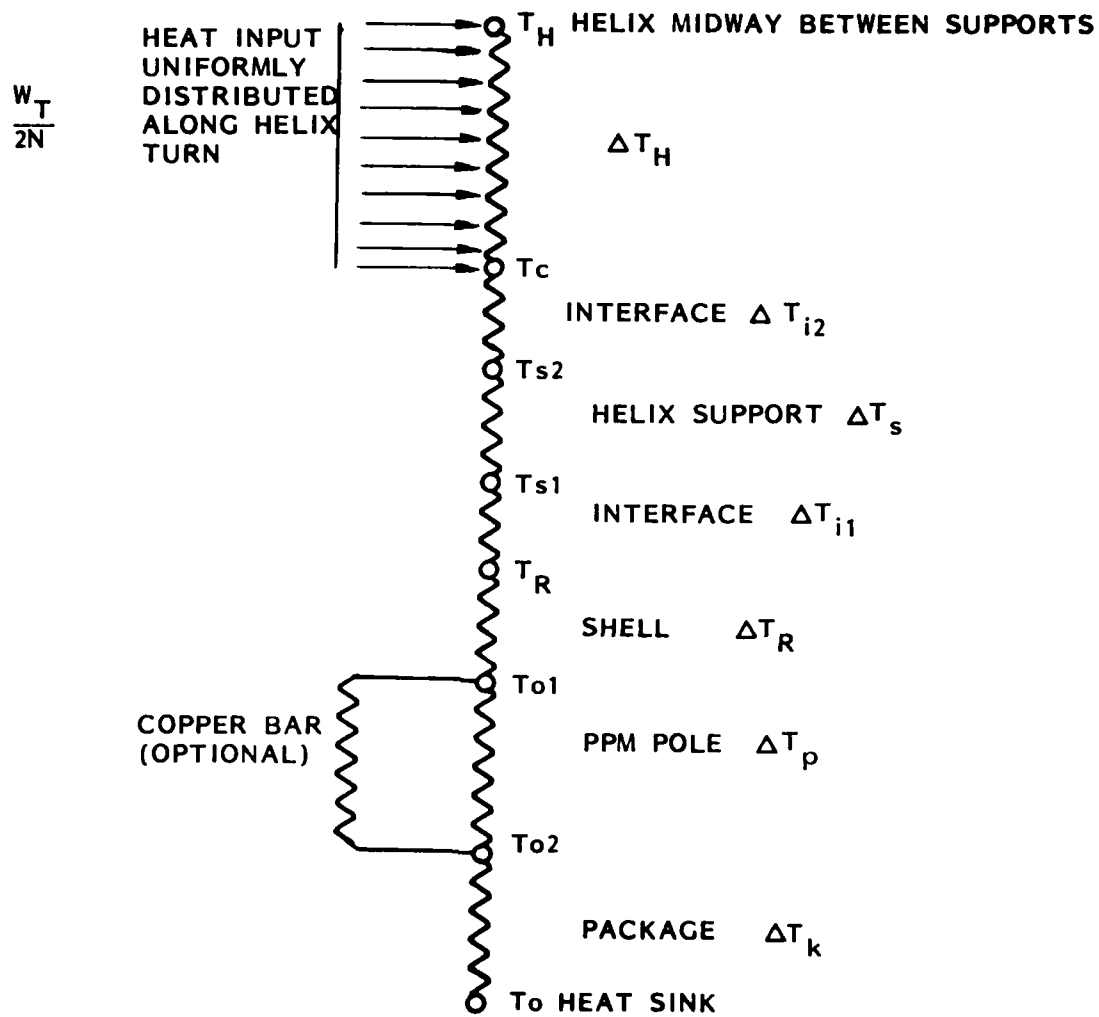
so that:

$$R = \frac{V}{I} \text{ becomes } R_T = \frac{(T_1 - T_2)}{q}$$

Then, working our way along the heat flow path from the external heat sink to the helix hot spot, the elements can be described by simple equations, as follows:

2.4.1 Package

$$\frac{\Delta T_k}{W_i} = \frac{L_k}{k_k A_k}$$



812402

Figure 5. Thermal Path-Helix to External Heat Sink.

where: ΔT_k = package temperature difference °C
 W_i = watts/ inch
 k = thermal conductivity watts inch $^{-1}$ °C

$$2.4.2 \quad \text{PPM Pole} \quad \frac{\Delta T_p}{W_i} = \frac{\ln \frac{r_2}{r_1}}{2 k_p t}$$

where: W_p = power dissipation per PPM cell

then, since $W_i = \frac{2W_p}{P_M}$ P_M = PPM period

$$\frac{\Delta T_p}{W} = \frac{\left(\ln \frac{r_2}{r_1} \right) P_M}{4 \pi k_p t}$$

2.4.2.1 Copper Heat Conduction Bars (optional, if used)

These modify the effective thermal resistance of the PPM poles by virtue of being in parallel with the poles so that the temperature difference across the poles becomes:

$$\frac{\Delta T_p}{W_i} = \frac{1}{\frac{4 \pi k_p t}{\left(\ln \frac{r_2}{r_1} \right) P_M} + \frac{A_B k_B}{L_B P_M}}$$

2.4.3 Shell

The thermal resistance of the shell is somewhat more complicated to describe in the form of a simple analytic expression. This is because the heat flows from the helix supports into the shell at a number of small discrete

contact points and then spreads out into the volume of the shell as it flows outward. The concept of thermal spreading resistance has been used⁽¹⁾ to calculate the heat flow from small cubical diamonds into a copper support block. This concept is valid for the case of a small high conductivity piece in contact with a large block of lower thermal conductivity material, and the equations for several geometries are given in Rohsenow and Hartnett⁽⁸⁾. For the idealized case of square area of contact of a diamond cube with a semi-infinite block of metal (with thermal conductivity = k_R), the equation for each element contact is:

$$\frac{\Delta T}{q} = \frac{\ln(4)}{\pi k_R b} = \frac{0.4413}{k_R b}$$

where:

b = size of the diamond cube

Thus, in the units we are using, for a helix supported by N diamond cubes per turn the thermal spreading resistance of the shell becomes:

$$\frac{\Delta T_R}{W_i} = \frac{0.4413 p}{N k_R b}$$

where:

p = helix pitch

For a helix supported by continuous diamond bars a different equation for thermal spreading resistance is necessary. This can be derived for the situation which typically exists in a PPM focused TWT where there are helix support bars which feed heat into the shell along lines of contact (of width = b), and the heat flows into the shell spreading and leaving the shell along the entire circumference. Subject to these conditions it can be shown that the thermal spreading resistance for each support bar to shell contact is given by:

$$\frac{\Delta T}{\left(\frac{q}{L}\right)} = \frac{\ln\left(\frac{2t}{b} + 1\right)}{2k_R}$$

where: t = shell thickness
 b = contact surface width

Thus, in the units we are using, for a helix supported by N diamond bars, the thermal spreading resistance of the shell becomes:

$$\frac{\Delta T_R}{W_i} = \frac{\ln \left(\frac{2t}{b} + 1 \right)}{2Nk_R}$$

This gives us a choice, depending on geometry, of one of two equations for thermal spreading resistance to represent the shell in the electro-thermal equivalent circuit.

2.4.4 Interfaces (Shell to Diamonds and Helix to Diamonds)

There also is a temperature difference across the interface between the diamond helix supports and the shell and the helix. This is the typical problem which exists at a contact between a dielectric and a metal member, and this was discussed in detail elsewhere in this report (see Section 2.3). The thermal interface resistance coefficient for diamond to copper plated tungsten is given by:

$$\rho = 0.00888 \text{ } ^\circ\text{C cm}^2 \text{ watt}^{-1}$$

So that at any interface we have

$$\frac{\Delta T}{W} = \frac{\rho}{A}$$

where: A = interface area
 W = power flow across that interface

Thus we then have the following equation in the units we are using for the different interfaces.

a. Diamond Cube Helix Supports

(N per helix turn)

Diamonds to Shell

$$\frac{\Delta T_{il}}{W_i} = \frac{\rho p}{b^2 N}$$

where:

p = helix pitch

b = cube size

Diamonds to Helix

$$\frac{\Delta T_{i2}}{W_i} = \frac{\rho p}{A^1 N}$$

where:

A^1 = effective contact area of diamond to helix tape (typically somewhat less than maximum possible area)

b. Diamond Bars Helix Supports

(N bars)

Diamonds to Shell

$$\frac{\Delta T_{il}}{W_i} = \frac{\rho}{b N}$$

where:

b = bar width

Diamonds to Helix

$$\frac{\Delta T_{i2}}{W_i} = \frac{\rho p}{A l_N}$$

as above

2.4.5

Helix Supports

The temperature difference across the diamond helix supports is given by a simple heat conduction equation, as follows:

a. Diamond Cube Helix Supports

(N per turn)

$$\frac{\Delta T_s}{W_i} = \frac{hp}{Nb^2 k_s}$$

where:

h = diamond height

b = diamond width

p = helix pitch

 k_s = diamond thermal conductivityb. Diamond Bar Helix Supports

$$\frac{\Delta T_s}{W_i} = \frac{2 hp}{Nb(w+p) k_s}$$

where:

w = helix tape width

2.4.6

Helix Tape

The temperature distribution along the helix tape will be parabolic with maxima midway between supports and minima at the supports. We can model

the helix by considering one element consisting of the section from one maximum temperature point to a support. This means that the helix is divided into $2N$ sections for N supports. The heat input to the helix tape is assumed to be uniformly distributed along the circumference of a turn and there is assumed to be no axial flow of heat. Then one section of the model is a standard case, as presented in many heat transfer texts, of a bar uniformly heated and supported at one end by a heat sink.⁽¹⁸⁾ The temperature distribution along the tape is parabolic and given by the equation:

$$T = -(T_H - T_c) \frac{X^2}{X_o^2} + T_H$$

where:

T = temperature at any location X
 T_H = temperature at hot point
 T_c = temperature at cold point (support)
 X = distance along tape from origin at hot point
 X_o = total tape length from hot to cold point

The temperature at the hot point is given by

$$\Delta T_H = \frac{2 \pi a}{2 w t^1 (2N) k_H} \left(\frac{W_T}{2N} \right)$$

where:

a = helix mean radius
 w = helix tape width
 t^1 = helix tape thickness
 N = number of helix supports
 W_T = watts per helix turn

This can be changed into the units being used for the rest of these calculations, as follows:

$$\frac{\Delta T_H}{W_i} = \frac{\pi a p}{4 w t^1 N^2 k_H}$$

where:

p = helix pitch

An interesting point to note is that the helix temperature difference is proportional to the inverse square of the number of helix support bars. Thus, for example, a well worthwhile design tradeoff could be to use four support bars instead of three and reduce the bar width to maintain the same total dielectric loading factor with a lower peak helix temperature. For helix support bars of high thermal conductive material, such as diamond, a substantial reduction in total dielectric loading could be achieved while also reducing the helix temperature by increasing the number of supports and reducing the total amount of support material used.

Since the normal method for measuring helix temperature rise during thermal tests is based on measuring the helix resistance change to obtain the average helix temperature, it is worthwhile rewriting the equation above to give average helix temperature difference, which is:

$$\Delta T_{Hav} = \frac{2}{3} \Delta T_H$$

so that

$$\Delta T_{Hav} = \frac{\pi a p}{w_i \cdot 6wt^1 N^2 k_H}$$

2.4.7 Calculations

Now that simple algebraic expressions are available for each of the thermal resistances in the thermal model, it is easy to calculate the helix temperature rise above that of the heat sink. The given quantities shall be:

1. The dimensions of the structure
2. The thermal conductivities of the various materials as a function of temperature
3. The heat dissipated in the helix in watts per linear inch
4. The heat sink temperature (fixed).

Then the successive temperatures are calculated working upward from the heat sink to the helix. Since the thermal conductivity of materials varies with temperature, the calculation of each temperature is done by an iterative procedure changing the thermal conductivity after each temperature calculation, then recalculating temperature, and repeating the process until convergence is obtained. The procedure converges in a few iterations so that it is quite practical for either hand calculation or on a computer. By proceeding upward in steps from the known heat sink temperature the entire calculation results in accurate values for each temperature including the variation of thermal conductivity with temperature. This calculation method has been used in this project, and the results are believed to give accuracy equal to or better than the much more complicated and expensive computer methods for solutions of Poisson's equation.

2.5 Diamond Properties and Procurement

2.5.1 Types of Diamonds and Properties

The different types of natural diamonds are as summarized below:

1. Type I diamonds have nitrogen as an impurity in percentages of 0.05% to 0.25%. These are further subdivided into:

Type IA in which the N₂ is present as platelets in the crystal lattice. Type IB in which the N₂ is present in substitutional positions in the crystal lattice.
2. Type II diamonds have no nitrogen in them. Type IIA is the purest form with less than 0.02% nitrogen and excellent electrical insulating properties (resistivity of 10^8 to 10^{17} ohm-cm). This is the kind which is shipped as heat sink grade. They are selected by the infrared absorption spectrum because nitrogen gives a strong absorption peak at 7.8 microns which is very weak or absent in type IIA diamonds. The electrical resistivity of heat sink grade is tested to be greater than 10^8 ohm-cm.

Type IIB is a semiconductor due probably to either aluminum or boron impurity. The resistivity is about 1 ohm-cm.

3. The relative occurrence of the types of diamonds as mined are found to be size dependent as follows:

<u>Size</u>	<u>Percent Type IIA</u>
0.01 carat	15%
0.1 carat	2 to 5%
1.0 carat	< 0.5%
10.0 carat	> 75%
100.0 carat	almost 100%

This means that if the heat sinks are made from very large diamonds the material cost greatly exceeds the labor cost. Conversely to make heat sinks from very small and very cheap stones requires high labor costs. Currently 10 carat or larger diamonds are used but the suppliers are trying to develop automated processes to use very small diamonds.

The properties of diamond are listed in Appendix A.

2.5.2 Fabrication of Diamond Parts

The extreme hardness of diamond makes it very difficult to make any parts which are not of the simplest shape. Conventional cutting, grinding, and polishing of diamond require the use of diamond powder impregnated wheels, tools, etc. Exotic techniques such as lasers, etc. have been reportedly used to drill holes etc. Here at Raytheon MPTD we have no suitable facilities for making parts out of diamond and we have relied upon outside specialists to supply parts. Foremost of these has been: Dubbledee Diamond Corp., 2 West 46th Street, New York, N.Y. 10036.

It has been necessary in designing diamond supported helices to plan to use sizes and shapes which are readily available at reasonable cost.

The most commonly available sizes have been cubes which are in quantity production for use as semiconductor heat sinks. It has only been necessary to pay a small additional charge to obtain cubes to the tolerances needed to obtain proper control of the dielectric loading factor in helix TWT's. These standard sizes are listed in Table I as supplied by Dubbledee.

Table I Standard Sizes

<u>Type</u>	<u>Size</u>	<u>1974 Price</u>	<u>Recent* Price</u>
Type IIA	1/2 mm x 1/2 mm x 1/2 mm	\$ 8.50 ea	\$ 9.35 ea
Type IIA	1/2 mm x 3/4 mm x 3/4 mm	\$12.00 ea	
Type IIA	3/4 mm x 3/4 mm x 3/4 mm	\$15.00 ea	\$16.50 ea
MHSC/C1	1/2 mm x 3/4 mm x 3/4 mm (metalized)	\$14.50	
HSX-1	0.5 to 0.8 mm high 0.75 mm rough dia.	\$ 1.35 ea	
HSX-2	Same as HSX-1 except type IIA	\$ 8.50 ea	
HSX-1S	0.015 in. high 0.050 in. rough dia.	\$ 1.35 ea	
HSX-2S	Same as HSX-1S except type IIA	\$ 8.50 ea	

The experimental helix assemblies constructed in Phase I of this program used the 3/4 millimeter diamond cubes listed above. Later, after discussions with Dr. Michael Seal of Dubbledee, they agreed to supply diamonds in the form of bars 0.5 mm by 0.5 mm by 4 to 6 mm long at a cost of \$15.00 per mm. These are ideal for TWT usage because they can be laid end to end to give a direct replacement for the conventional beryllia or boron nitride helix support rods. All diamond supported helix work at Raytheon since late 1976 has used these bars, and the experimental helix assemblies constructed in Phase 2 of this program were built using bars.

* These two sizes of cubes plus the bars are the only ones which have been used in this program, the other sizes are listed for reference only.

2.5.3 Alternative Materials

There are several alternative materials which are also highly thermal conductive dielectrics and might be usable for TWT helix supports. These were investigated and after inquiries it was decided that they are not yet ready for TWT helix support usage. A brief summary follows:

2.5.3.1 Boron Nitride

Boron nitride theoretically can be made in the same crystalline forms as carbon. Thus it has similar properties to carbon in each of its crystalline forms.

Cubic boron nitride has the same crystal lattice as diamond and theoretically has very high hardness and high thermal conductivity. Unfortunately, it is not practical at this time for our usage. An extensive literature search and communications with Dr. Glenn Slack and Dr. R.E. Hanneman of General Electric established that at this time the G.E. cubic BN cannot be manufactured to have good dielectric properties nor can the full theoretical thermal conduction of it be achieved practically.^(9,10)

Anisotropic boron nitride (Boralloy*) and an even more highly oriented version are similar to pyrolytically deposited carbon in properties. The thermal conductivity is about 17% that of copper, and, therefore, not nearly as good as natural diamond.

2.5.3.2 Synthetic Diamond

The various types of true synthetic diamonds contain large amounts of impurities which decrease the thermal conductivity and drastically hurt the dielectric properties. There appears to be little prospect for improvement in the near future. The so-called "synthetic diamond gems" are actually other substances such as YAG and have very low thermal conductivity.

* Trade name of Union Carbide Corp.

2.5.3.3 Megadiamond*

Another possible material which would seem to be useful is "megadiamond" manufactured by Megadiaomond Industries Corporation. This consists of a mass of natural diamond powder which is pressed in a mold and sintered at very high temperature and pressure to form a material which has many of the properties of natural diamond crystals. It is a polycrystalline material similar to naturally occurring carbonados. Dr. Bill J. Pope of Megadiamond Industries supplied a sample which we found to have poor dielectric properties and to be mechanically quite weak. Later work is reported to have improved this material's properties, and it should be kept in mind for future usage.^(11,12,13)

It is suggested that progress on both cubic BN and megadiamond be monitored because it is quite probable that improvements eventually will be made in the properties of both of these materials such that they might be suitable alternatives to natural diamond in a few years.

*Trade name Megadiamond Corp.

3.0 EXPERIMENTAL STUDY OF DIAMOND SUPPORTED HELIX

The original work on the diamond supported helix was based upon the assumption that the structure would consist of a copper helix brazed to metalized diamonds which are brazed to a copper shell. As described above several structures were built using this concept but with difficulty. The design approach in which the diamonds hold a copper plated tungsten helix in compression was adopted for the low band millimeter wave TWT, and has been successful. An alternative design approach in which a diffusion bond of the helix to the diamonds is made using an alloy with high copper content and a small percentage of active metal (such as zirconium) also appears to have promise. Accordingly, the experimental work was planned to compare these two construction methods in Phase 1 by building and testing several helix assemblies of each type. The work in Phase 2 then was devoted to experimental tests of the heat transfer from the diamond supported helix assembly out through a PPM focusing structure.

3.1 Phase I Comparison of Bonded versus Compression Helix Structures

In order to compare the relative merits of the different types of helix construction it was planned to build several assemblies of each of the two types of construction. As described above, there are many methods which could be used to build a diamond supported helix. The most promising methods are

1. Copper helix brazed to the diamonds
 - a. Metalized diamonds
 - b. Active alloy solder
2. Copper plated tungsten or molybdenum helix held in compression within the diamonds .
3. Copper alloy helix diffusion bonded to the diamonds.

The brazed type of helix has been tried in previous work, and has problems with controlling the amount of spreading of the metalizing and/or solder

unto surfaces where clear dielectric is required. Therefore, in this program the latter two structural methods (compression and diffusion bonding) were investigated. The criteria for final choice of the optimum design approach were:

1. Power handling performance as measured by passing high AC current through the helix. (Actual performance is a more practical criterion than theoretical capability.)
2. Practicality of construction based on actual experience in building sample helix assemblies.
3. Electrical characteristics (if any difference is found between the different constructions).

For this study helix dimensions were chosen which would be useful in a high CW output power solenoid focused I-band TWT. This was so that practical dimensions would be used in the building of sample structures. By working in terms of a possible solenoid focused TWT the measured power handling capability also represents the ultimate capability of the diamond supported helix independent of any other limitations imposed by a PPM structure (which was studied in Phase 2).

3.1.1 Test Assembly Design

3.1.1.1 Electrical Design

The basic helix dimensions were calculated for an I-band TWT capable of 2500 watts output power using the standard small signal and large signal computer programs which Raytheon uses for all TWT design work. The basic design parameters are listed below:

Helix Mean Radius	0.052 inches
Helix ID	0.097 inches
Helix Tape	0.007 inches x 0.035 inches

Helix Pitch (output end)	0.0575 inches
(input end)	0.0625 inches
Barrel ID	0.172 inches
Helix Supports (3 per turn)	0.030 inches diamond cubes
Beam Radius	0.027 inches
Beam Voltage	10.5 kV
Beam Current	1.0 A

Another advantage of the use of diamond helix supports is that they can be smaller than conventional dielectric supports so that the electrical characteristics can be good. This is shown for this design by the velocity and coupling impedance as plotted in Figures 6 and 7.

3.1.1.2 Mechanical Design

The mechanical design concept for the thermal test helix assemblies was one which had been used previously to test K-band helix assemblies. The circuit block is made in two halves which fit together to enclose the helix with the required compression. A drawing of the end view of the helix assembly is shown in Figure 8 and parts for such an assembly are shown in Figure 9.

The assembly has been designed so that one can be constructed using either the tungsten helix held in compression of design No.1, or the copper helix bonded in place of design No.2. This can be seen by referring to the list of materials in Figure 10, where item 6, the helix-shell assembly, lists two alternative part numbers, one for each design. The helix-shell assembly is a separate sub-assembly, which is constructed first, and which then forms the core onto which the other parts are brazed to make the helix assembly for thermal tests. Thus, once the helix shell subassembly has been made, the rest of the helix assembly is constructed the same for either design No. 1 or design No. 2.

Referring to Figure 10 again the helix-shell assembly (item 6) is brazed between two water cooled copper blocks (item 5). Water enters one

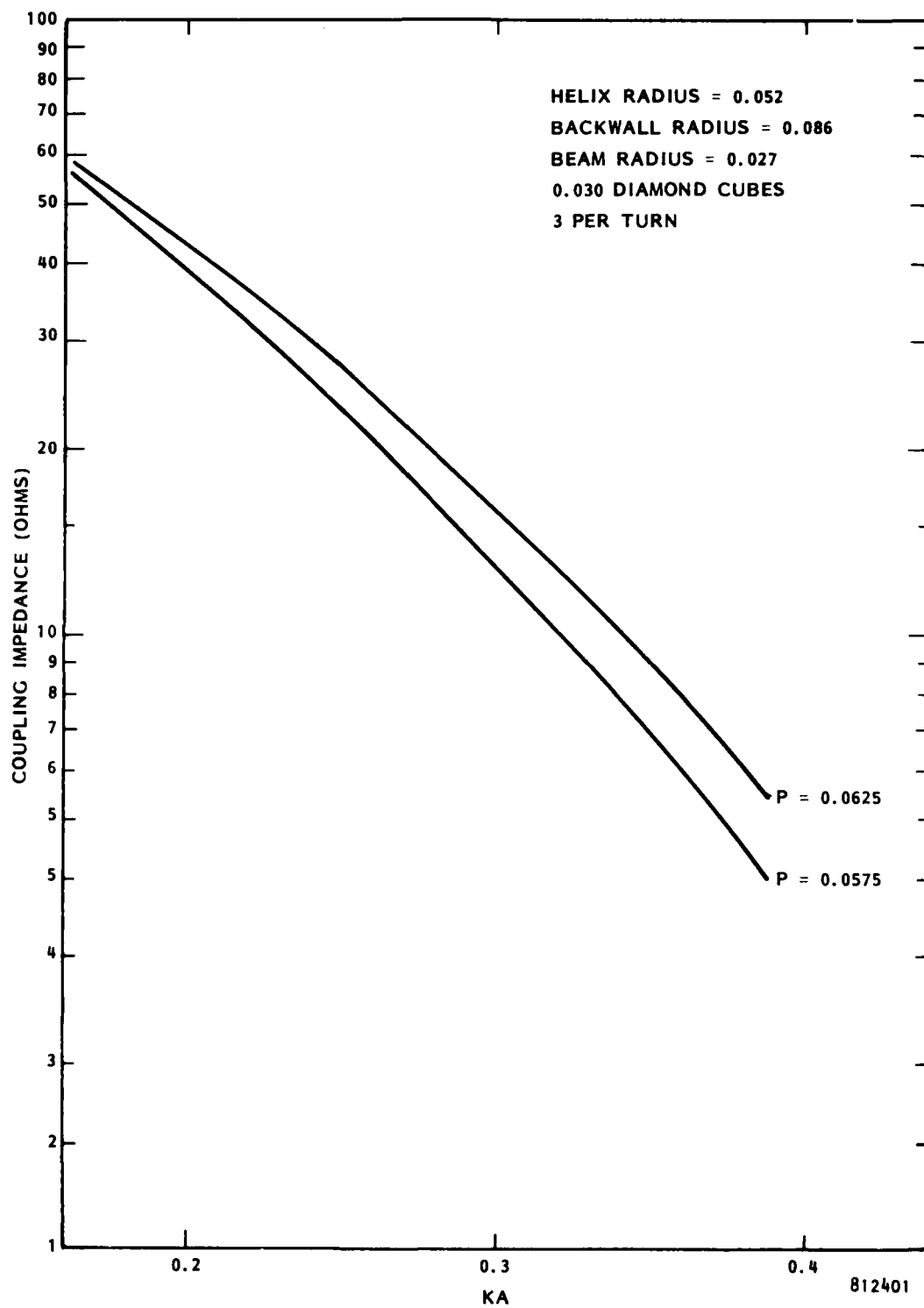


Figure 6. Coupling Impedance.

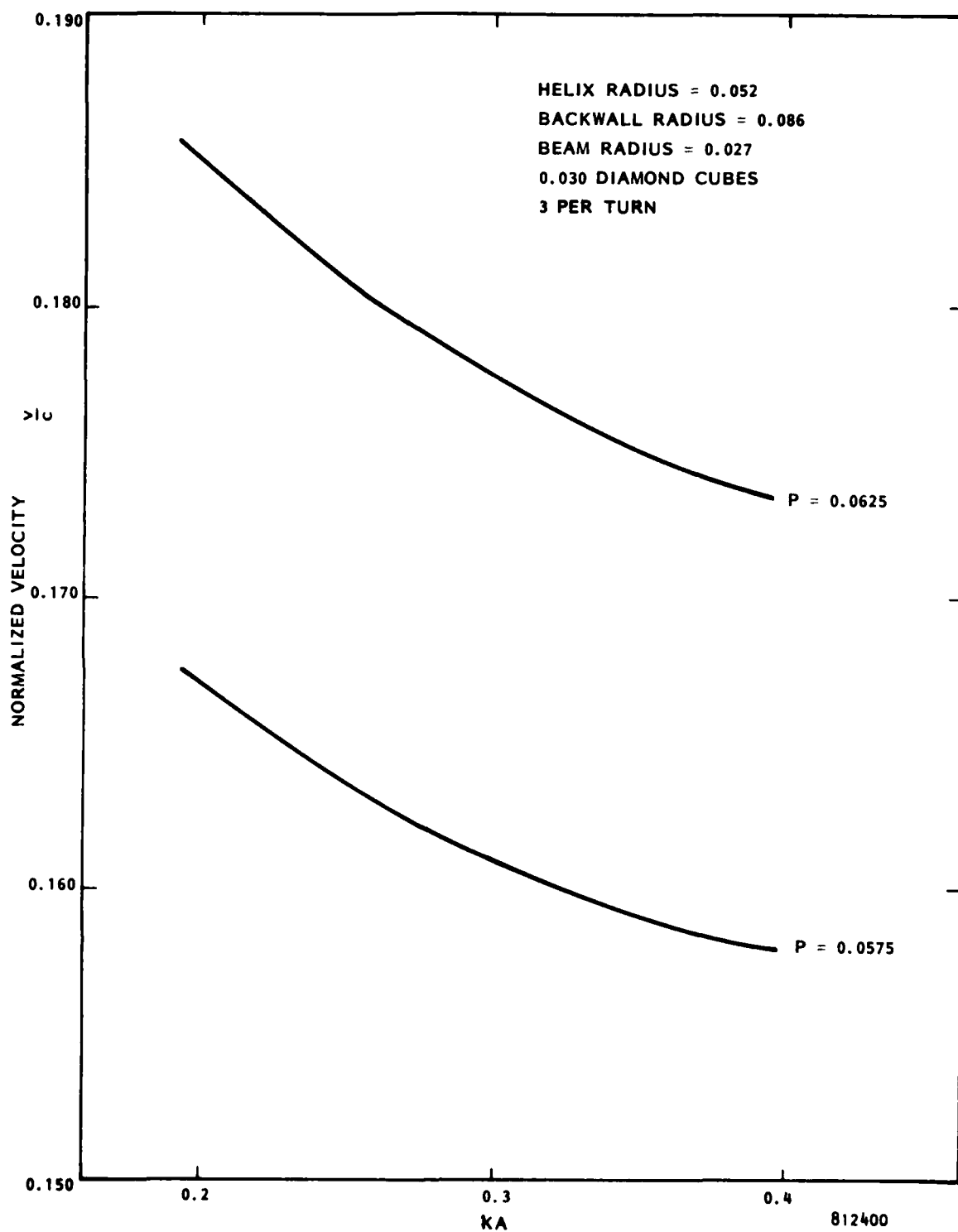
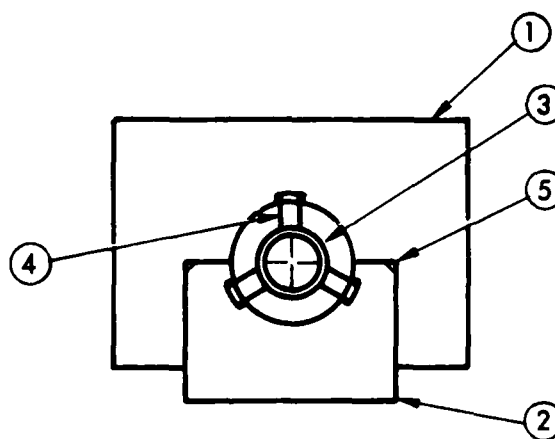


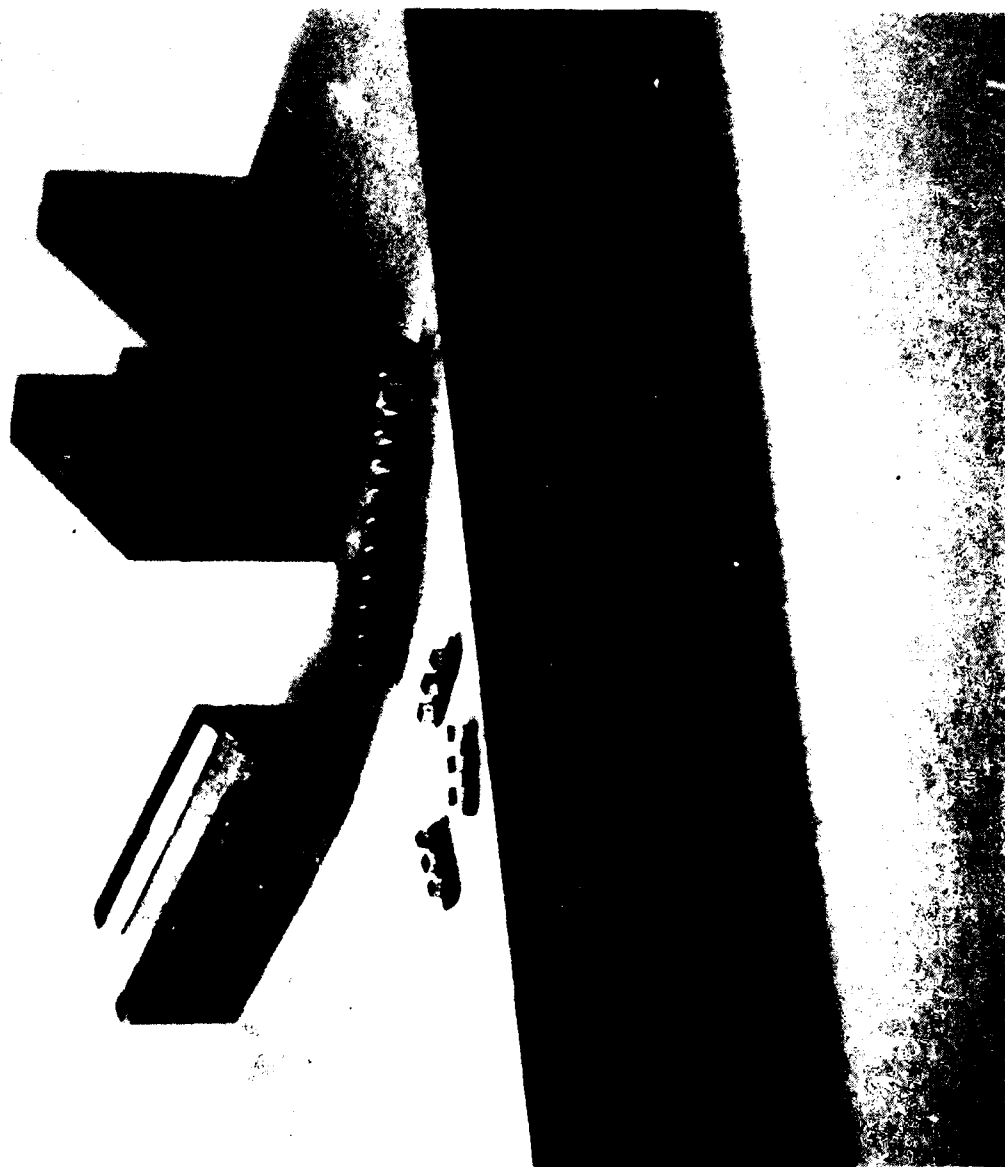
Figure 7. Helix Velocity.

- 1 - UPPER CIRCUIT BLOCK
- 2 - LOWER CIRCUIT BLOCK
- 3 - HELIX a - COPPER TAPE
 b - TUNGSTEN TAPE
- 4 - HELIX SUPPORT SUB-ASSEMBLY
- 5 - NICORO SOLDER



812403

Figure 8. Helix-Shell Assembly.



74-71682

Figure 9. K-Band Test Helix Parts.

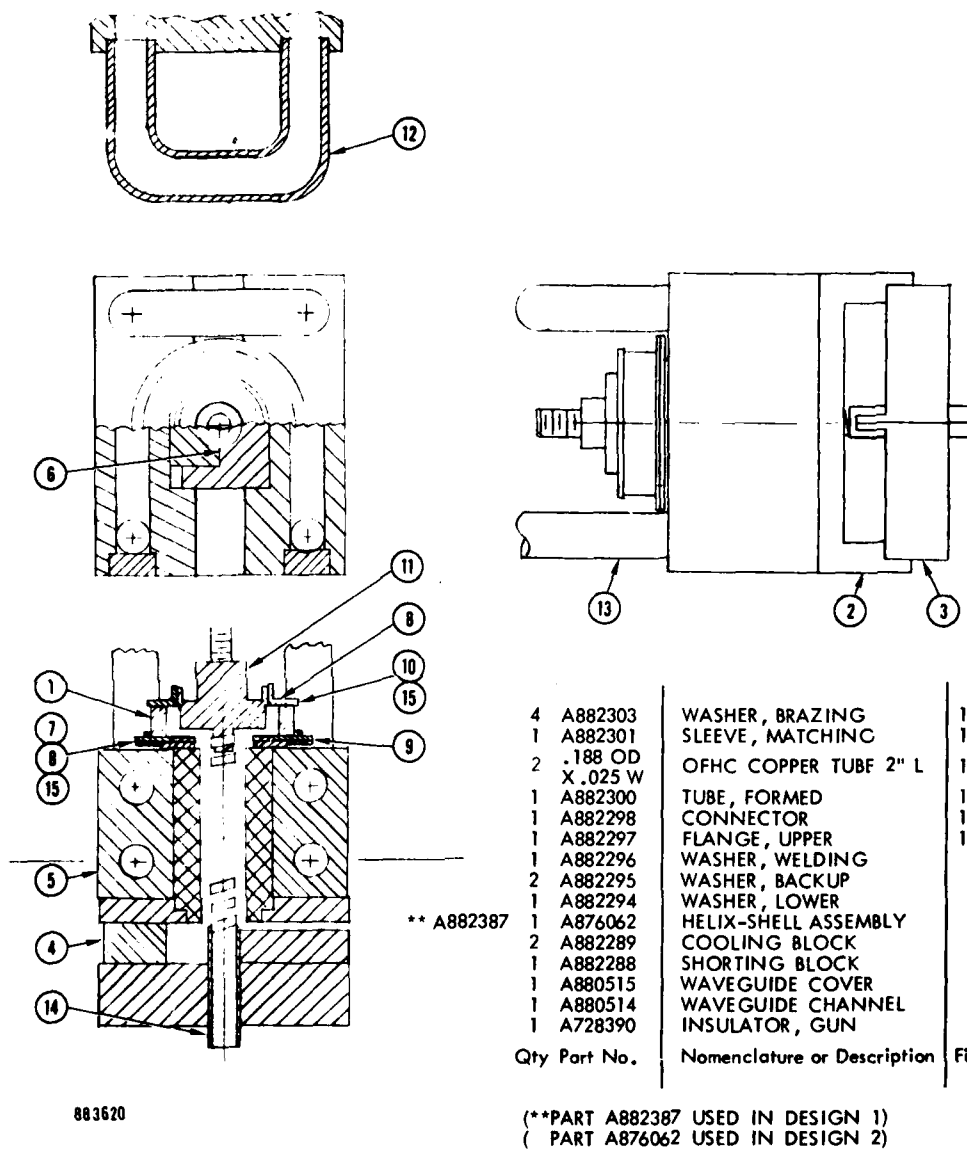


Figure 10. Helix Assembly (Thermal Test)

block through a tube (item 13), flows through the channels in the block, crosses over to the other block via item 12, flows through that block and out through another tube. Onto one end is brazed a direct helix to waveguide transition which grounds the helix for dc through the braze to item 14 and the main body of the waveguide. This waveguide transition also furnishes an rf connection to the helix for measurements of the phase velocity and impedance. Onto the other end of the helix is brazed a copper connector (item 11) supported by a ceramic insulator (item 1). This gives the means for feeding dc current into the helix to generate heat and measure the power dissipation capability of the helix.

Figure 11 shows a photograph of a completed thermal test assembly. Constuction of a total of six thermal test assemblies was planned, three of each type. The results are given in the following sections.

3.1.2 Compressed Tungsten Helix Assemblies

In this design the helix is wound using tungsten tape, fired to set it, ground to give a uniform outside diameter, then flats are ground 120° apart for the diamonds to rest against. A thick copper plating is put on the helix to give the soft interface material for the diamonds to press into. The helix is installed in the assembly, pressure is applied to the circuit block halves to compress the helix, and the block halves are brazed together. Three assemblies were made of this type. The first was over compressed with damage to the helix. Brazing problems resulted in a loose helix in the third. The second one was good and it was subjected to full thermal testing, the results of which are described below.

Calculations for the tungsten helix had predicted an average helix temperature rise of 250°C and a helix hot spot temperature of 321°C at a power dissipation of 1000 watts per inch. Also, in these calculations it was predicted that at the anticipated operating condition of 2500 watts rf power in an actual TWT the helix power dissipation would be 945 watts per inch. Thus, this helix design was predicted to be capable of operation in excess of 2500 watts rf power output.

PT-5413

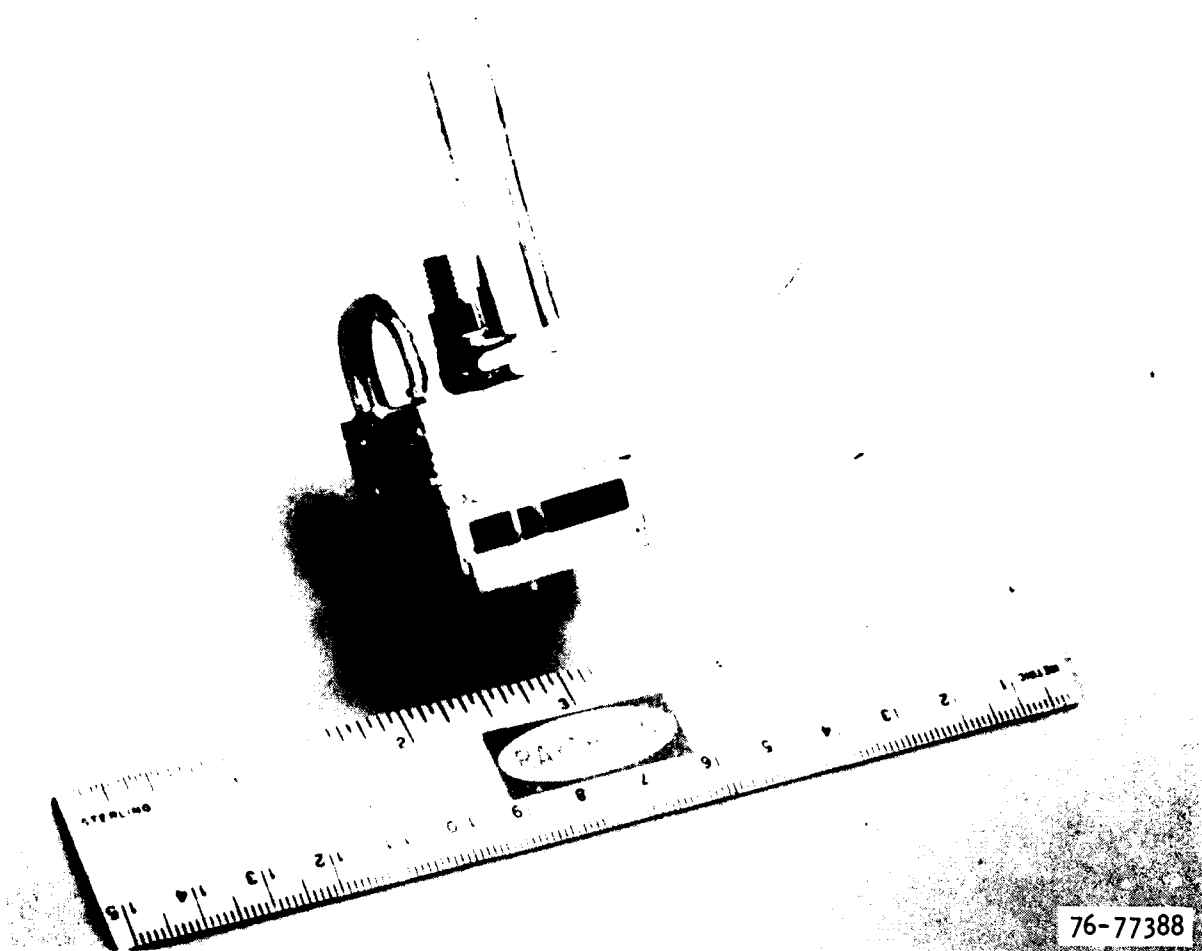


Figure 11. Thermal Test Assembly.

The helix assembly was thermal tested in a vacuum bell jar with cooling water circulating through the cooling passages in the block. A heavy bus bar connection was made to the threaded stud, which is brazed to one end of the helix, and this was brought out to one side of a variable high current 60 hertz supply. The return circuit was through the block to ground. The voltage drop across the helix was measured between two probes, one welded to the helix at the braze to the current feed in stud, the other welded to the block close to the grounded end of the helix. Each probe consisted of two wires (chromel and alumel) so that by switching to a thermocouple bridge the temperature could be measured at these two points.

Three test runs were made on this helix assembly. In each run the current feeding through the helix was increased in steps, allowing suitable time at each step for all temperatures to stabilize. The resistance of the helix and the power input to the helix were calculated at each step from the measured voltage and current and a graph of resistance versus power was continuously updated. Deviation of this graph from a straight line (linear) relationship between resistance and power should give advance indication of impending burnout. In addition, using the known variation of resistance of tungsten versus temperature, the average helix temperature rise was determined from the measured helix resistance, and this is plotted in Figure 12.

Also plotted in Figure 12 is the theoretical average helix temperature versus input power. This was calculated using the method described in Section 2.4 with temperature variation of thermal conductivity included for each material. The thermal pressure interface resistance was assumed to be constant at the value of $0.009^{\circ}\text{C cm}^2\text{watt}^{-1}$ in these calculations. In Figure 12 it can be seen that the experimental temperature rise curve is slightly above the theoretical for low power dissipation and below for high power dissipation. This can easily be explained by a reduction in the thermal contact resistance as the helix heats up and expands so as to press harder against the diamond supports. In general,

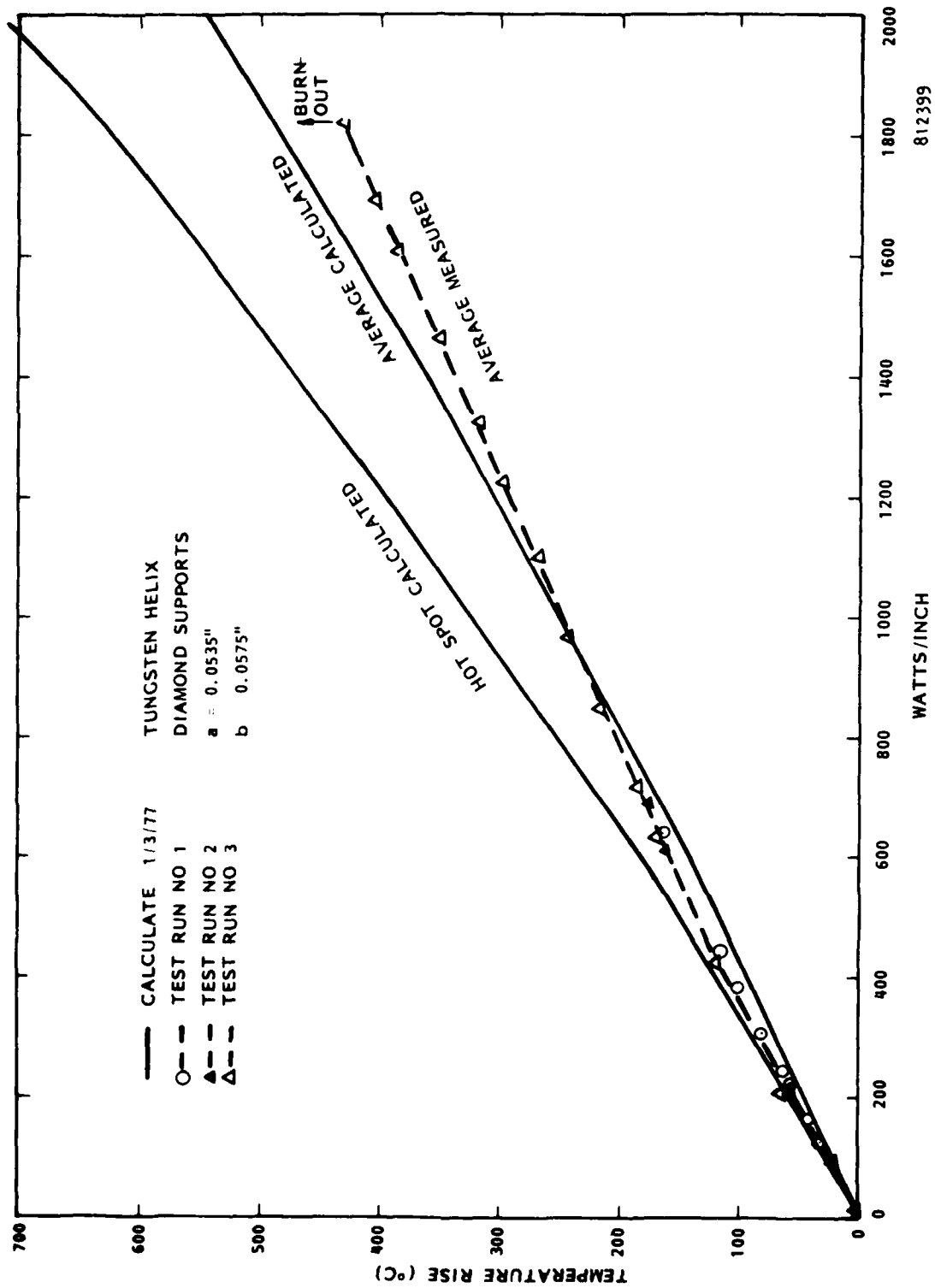


Figure 12. Thermal Test Results.

however, the measured temperature rise agrees well with the theoretical rise.

In the third test run the power input to the helix was deliberately increased to the burnout point in order to find out what would happen. As before, the input power was increased in steps with a wait each time for temperatures to stabilize. At 1460 watts per inch power input a slow rise in pressure was noted after 7 minutes at this power. At 1610 watts per inch power input the pressure rose at first and then dropped, indicating outgassing of some part. At 1700 watts per inch the pressure held steady indicating no further outgassing. Also at 1822 watts per inch the pressure was steady; and, as at all other points, the resistance versus power input was still an exact straight line function. However, after three minutes operation at 1822 watts per inch, the helix suddenly open circuited without any prior warning (i.e. there was no outgassing). The average helix temperature rise was 431°C at this point with an estimated hot spot temperature of 630°C . Subsequent scrap analysis of this assembly showed that the burnout had occurred at the first turn in from the junction with the current feed-in rod. Previous deliberate burnouts of K-band helices have also shown the same failure point just adjacent to the connection to the coaxial center conductor.

This end of the helix is not as securely held in position as the opposite end, which is brazed to the ridge waveguide center conductor so that it cannot move. Further examination of the burned out helix showed that at the coaxial input end it had shifted axially, due to differential expansion, so that the last turn was only making about 50 percent contact with the diamond cubes. The conclusion is clear. The end of the helix should be held securely in place as when brazed to the ridge waveguide transition; and the use of continuous diamond support bars is very desirable so that small axial movement of the helix cannot affect the contact of the helix to the supports.

Certainly, these test results show that the tungsten helix design is capable of operation at the required power level, and there is substantial safety margin between the planned operating point (945 watts/inch, 340°C hot spot temperature) and the burnout point (1822 watts/inch, 631°C hot spot

temperature). Based on this it is safe to conclude that the desired rf output power of 2500 watts cw can be achieved with a tungsten helix held in compression by 3 support diamonds per turn. Thus, we can conclude that this design approach will give acceptable performance, and it can be built with reasonable ease.

From these results we also conclude that both ends of the helix of an actual TWT should be firmly anchored to something such as a waveguide ridge so that heating and cooling cycles cannot cause the helix to move axially. Unfortunately, for tests using high currents at 60 hertz to heat the helix, such a connection can only be used at one end of the helix while the other end cannot be grounded. Thus, low frequency high current tests would appear to be an unrealistically severe method for determining the power handling capability of a helix. This means that while these tests indicate a 1.7/1 safety factor for ability to operate at 2500 watts cw, the actual safety factor probably is considerably better.

3.1.3 Bonded Copper Helix Assemblies

As described previously, copper helices brazed to metalized diamonds were constructed several years ago and shown to have high power dissipation capability. However, the difficulties encountered in confining the metalizing and solder to just the brazing area made this approach seem less desirable even though it has the highest power handling capability of all. A modified version of the brazed helix design is to use an active metal alloy which will bond by solid state diffusion directly to the diamonds. There are several such alloys consisting of copper with a small percentage of an active carbide former such as titanium or zirconium. The alloy of copper with a small fractional percentage addition of zirconium is readily available and has thermal conductivity over 90% that of pure copper. Raytheon had previously developed a process for directly bonding this alloy to diamond which required heating in a vacuum under pressure to achieve bonds with strength equal to the strength of the metal. Accordingly, a helix design using this bonding method was investigated.

Assembly fixtures were designed to hold the helix under compression in contact with the diamond supports during the required vacuum firing cycle. With proper temperature and time the zirconium in the helix tape bonded to the diamonds very well. Then the mandrel was removed by dissolving it in acid so that no mechanical strain was put on the helix. The result was a soft copper helix bonded to three diamond supports per turn, which were bonded to a copper outer block. Pull tests showed that the bonds were of the necessary strength. However, it was found that the fit of the diamonds to the helix, temperature, time and vacuum all affected the quality of the helix to diamond bonds. Several assemblies were built before a satisfactory one was obtained. The construction of a helix assembly of this type required painstaking care. The third helix assembly was acceptable and was subjected to thermal tests.

Figure 13 shows the measured average helix temperature rise for three test runs compared to the calculated average and hot spot temperatures. It can be seen that the measured temperature agrees quite well with the calculated temperature. Also, by comparison with Figure 12, the slope of the temperature versus power curve can be seen to be considerably lower, showing that this helix construction does give better thermal conduction out of the helix.

Unfortunately, on the third test run the helix temperature suddenly rose rapidly and burn out occurred at 1200 watts per inch input power. This is considerably less input power than the compressed tungsten helix was able to dissipate. Scrap analysis showed that the third helix turn in had melted directly over one of the diamond supports, indicating that the bond of this helix turn to that diamond had failed. Pull tests showed that several other helix to diamond bonds were considerably weaker than they should be. Apparently, due to mechanical tolerances, etc, some of the diamond to helix bonds were weak; and, after three thermal cycles, one failed allowing a helix turn to overheat and burn out.

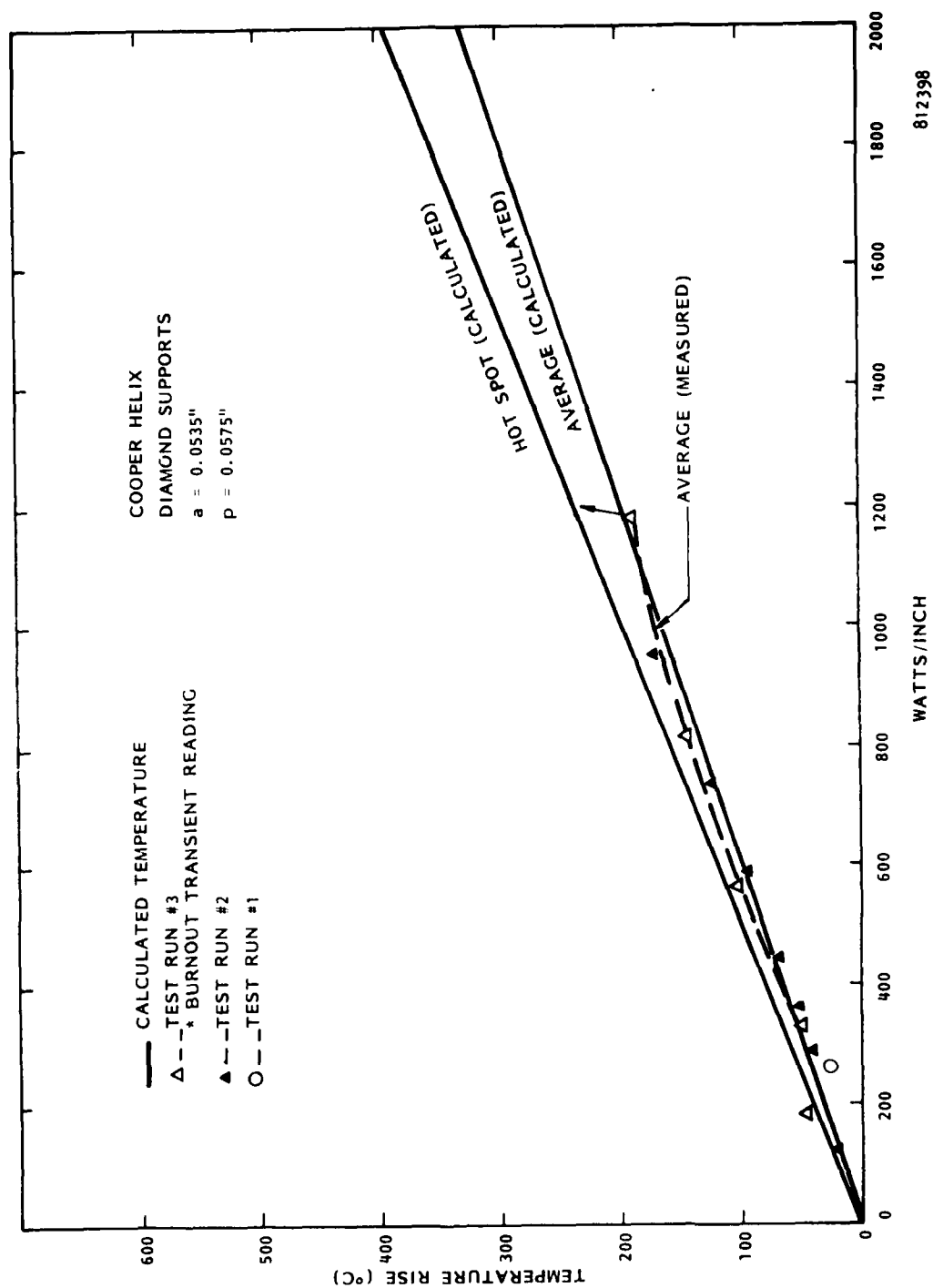


Figure 13. Thermal Test Results.

It was concluded that, even though a copper helix bonded to diamond supports has the highest theoretical power dissipation capability, this construction does not seem to be practical for actual use in TWT's. The basic problem is that the bonding process requires very careful control and there is no non-destructive test for verifying that all helix to support bonds are good in a particular helix assembly.

3.1.4 Discussion of Results

Three basic methods for constructing a diamond-supported helix have been examined. These are:

1. Copper helix brazed (using solder which melts and flows) to the diamond supports.
2. Copper helix bonded (by diffusion of an active metal) to the diamond supports.
3. Tungsten helix (with thick soft copper plating) held in compression by the diamond supports.

As a result of the tests reported above it has been concluded that the copper plated tungsten helix held in compression is the best practical design since the full theoretical power capability was achieved with this approach. Both the brazed and the bonded copper helix construction have problems due to the difficulty in controlling the process so that construction of such helix assemblies could be prohibitively expensive. The compression tungsten helix requires normal construction control of tolerances and is self compensating for minor variations. This occurs if one helix turn is slightly less tightly held so that it will heat slightly faster, expand more, and make a better thermal contact to the diamonds. The test results bear this out.

The brazed copper helix, previously tested, survived all thermal dissipation tests and showed little temperature rise; but, during construction, much labor was required to clean undesired metalizing from the exposed surfaces of the diamonds. Thus, a copper helix brazed to metalized diamonds will give the highest possible power dissipation capability, if this expensive construction method can be accepted, or if a more controllable metalizing process is developed. The solder tends to flow and fill in gaps due to mechanical tolerances.

The bonded copper helix has the same basic power dissipation capability as the brazed copper helix; but reliable control of the bonding process was not achieved, due to variations in dimensional tolerances.

The test results also verify the accuracy of the thermal resistance model for calculating helix temperature rise. This model breaks the thermal path down into an adequate number of elements for each of which an accurate equation can be written to describe its thermal resistance. The key to choosing the boundaries defining the elements is to take into account the natural symmetries of the structure, so that each boundary between material is along a line of constant temperature. The use of thermal spreading resistance for the heat flow out of the diamonds into the shell improves the accuracy of the calculations.

For comparison purposes the temperature rise was calculated for copper and tungsten helices with diamond and with beryllia supports (three per turn). The beryllia to copper thermal interface resistance was assumed to be 0.020 which is twice as good as the value of 0.0456 quoted in Section 2.3.1-4. The results are shown in Figure 14, where average helix temperature is plotted versus power dissipation. This comparison shows the advantages of the diamond supports to be two to one for tungsten helix and 2.5 to one for a copper helix. With four supports per helix turn, there is less temperature difference along the helix turn and there is about a 10 percent increase in the advantage of diamond helix supports.

Another interesting comparison is to examine the temperature profile from the helix hot spot to the heat sink. This has been done in Figure 15,

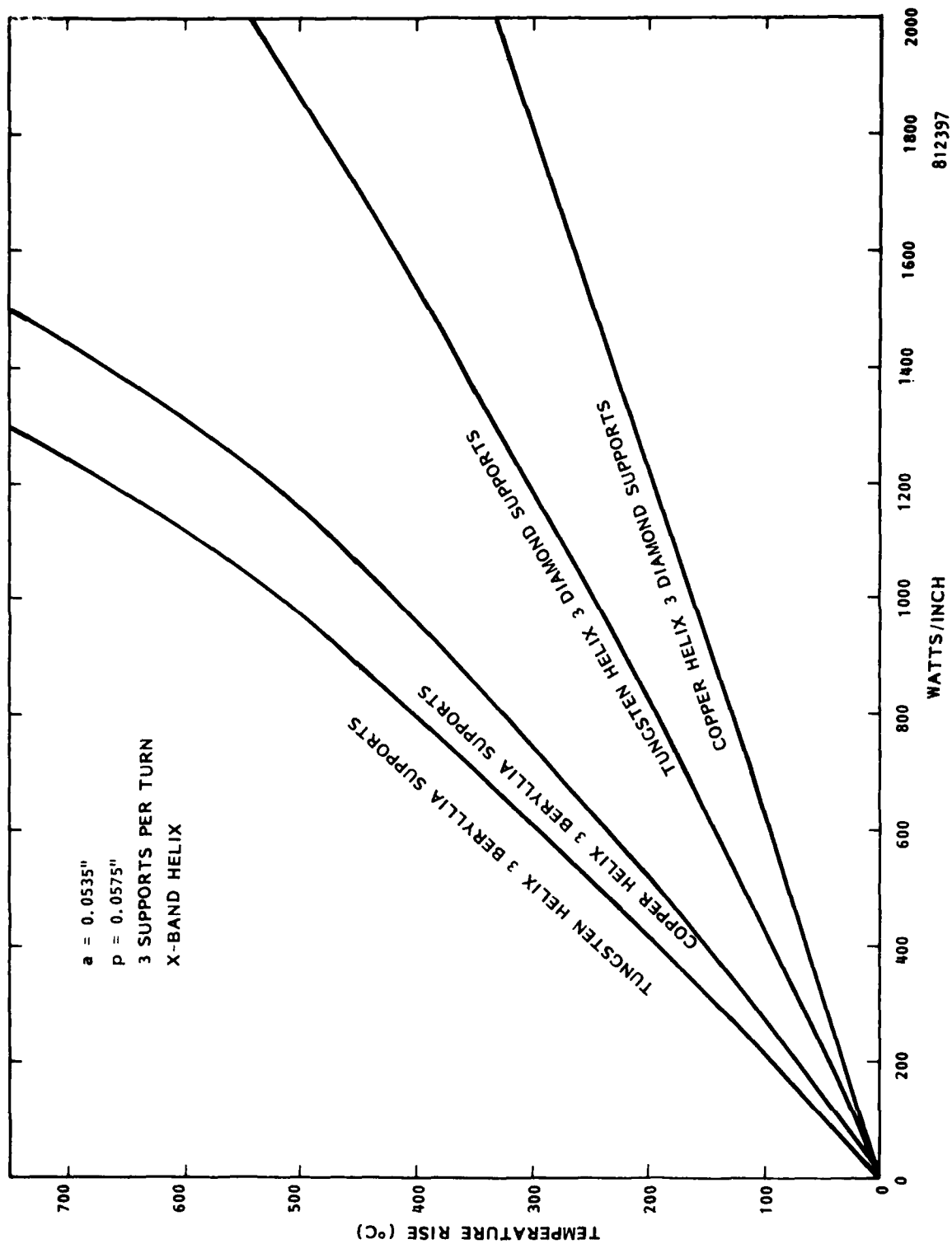
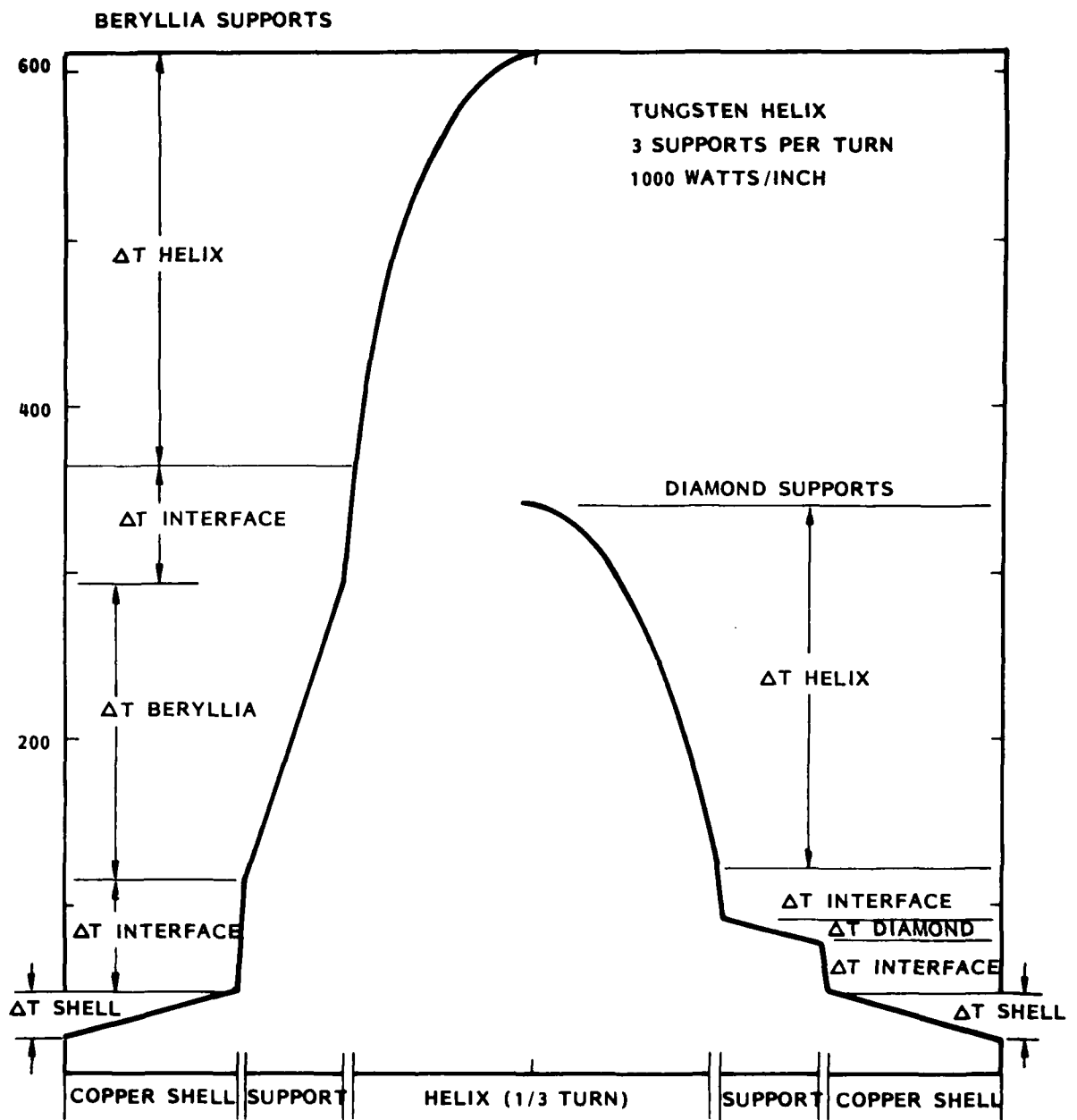


Figure 14. Helix Temperature vs Power Dissipation.



812392

Figure 15. Temperature Profiles.

where beryllia and diamond helix supports are compared for a tungsten helix dissipating 1000 watts per inch. This immediately shows how much of the temperature rise occurs in each element of the assembly. Note that ΔT helix is larger when beryllia supports are used even though the helix dimensions are not changed. This is due to the increased thermal resistance of the helix tape because the basic helix temperature is higher. The calculation method, by including variation in thermal resistance with temperature, shows this effect correctly.

3.1.5 Conclusions

As a result of the preceding discussion, the following conclusions may be reached.

1. The copper plated tungsten helix held in compression by diamond supports is the most practical high power dissipation helix assembly.
2. The copper helix brazed to diamond supports has the highest power dissipation capability but is more difficult to build.
3. The thermal resistance analogue gives an accurate and easy method for calculating helix temperature rise and is recommended for this purpose over more complicated computer programs.

3.2 Phase 2 Diamond Supported Helix in a PPM Focusing Structure

A valid question with regard to a helix assembly design is what its power dissipation capability will be when enclosed within a periodic permanent magnet (PPM) focusing system. The heat dissipated in the helix then has to flow out through the additional thermal resistance of the iron pole pieces of the PPM focusing system. The temperature difference across the poles can very often be as large as the temperature difference between the helix hot spot and the shell. Thus, in Phase 2 it was decided to investigate power dissipation capability of a helix within a PPM focusing system. For convenience it was decided to build experimental assemblies with dimensions suitable for a TWT which would cover J through K bands. The design and test results are described below.

3.2.1 Helix Design-Electrical

The electrical design dimensions of the helix and PPM structure which was chosen as the prototype for this series of tests are listed below:

Helix Mean Radius	0.024 inches
Helix ID	0.043 inches
Helix Tape	0.005 x 0.020 inches
Helix Pitch	0.040 inches
Barrel ID	0.107 inches
Helix Supports (3 per turn)	0.020 inches square diamond bars
Pole ID	0.135 inches
Pole OD	0.608 inches
Pole Thickness	0.0375 inches
Magnet OD	0.750 inches
Magnet Thickness	0.0875 inches
PPM Period	0.250 inches
Peak Field on Axis	4400 gauss

3.2.2 Helix Design-Mechanical

Within the constraints established by the electrical design dimensions the mechanical and thermal design was chosen. The helix was made of 0.0045" x 0.020" tungsten tape with 0.0005" copper plate. The supports were three 0.020" square diamond bars which held the helix in compression created by wrapping tungsten wire close wound over a split shell. This then is gold brazed to permanently set the tungsten wrapping wire in place and the poles are slipped over the assembly and brazed in place. The construction sequence is outlined in Figure 16. Several of the diamond bars are shown in Figure 17, and a close up end view of a wire wrapped helix assembly is shown in Figure 18. The parts for a circuit assembly and a completed circuit assembly are shown in Figures 19 and 20.

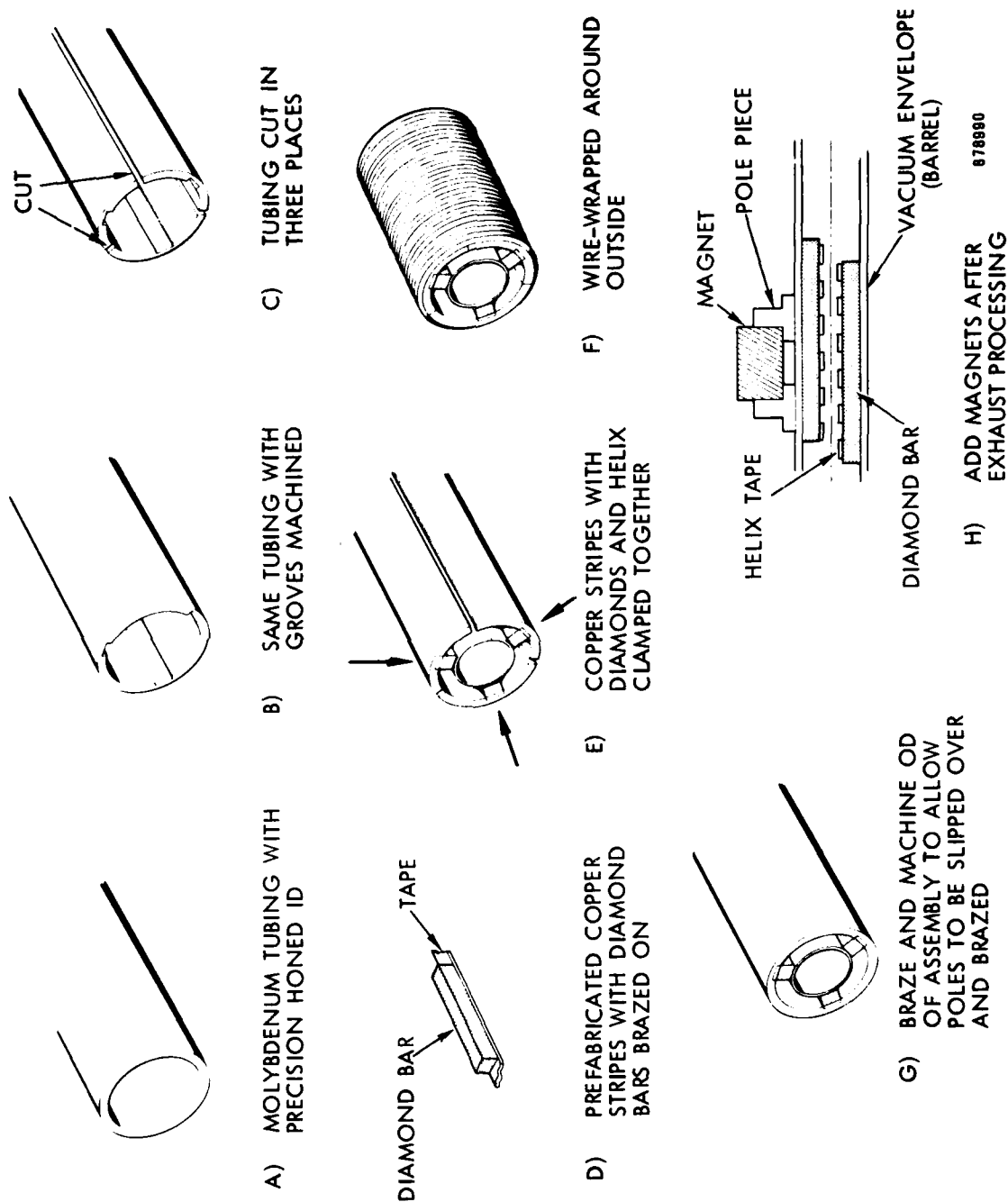


Figure 16. Assembly Sequence.

PT-5413

CN-21-2681

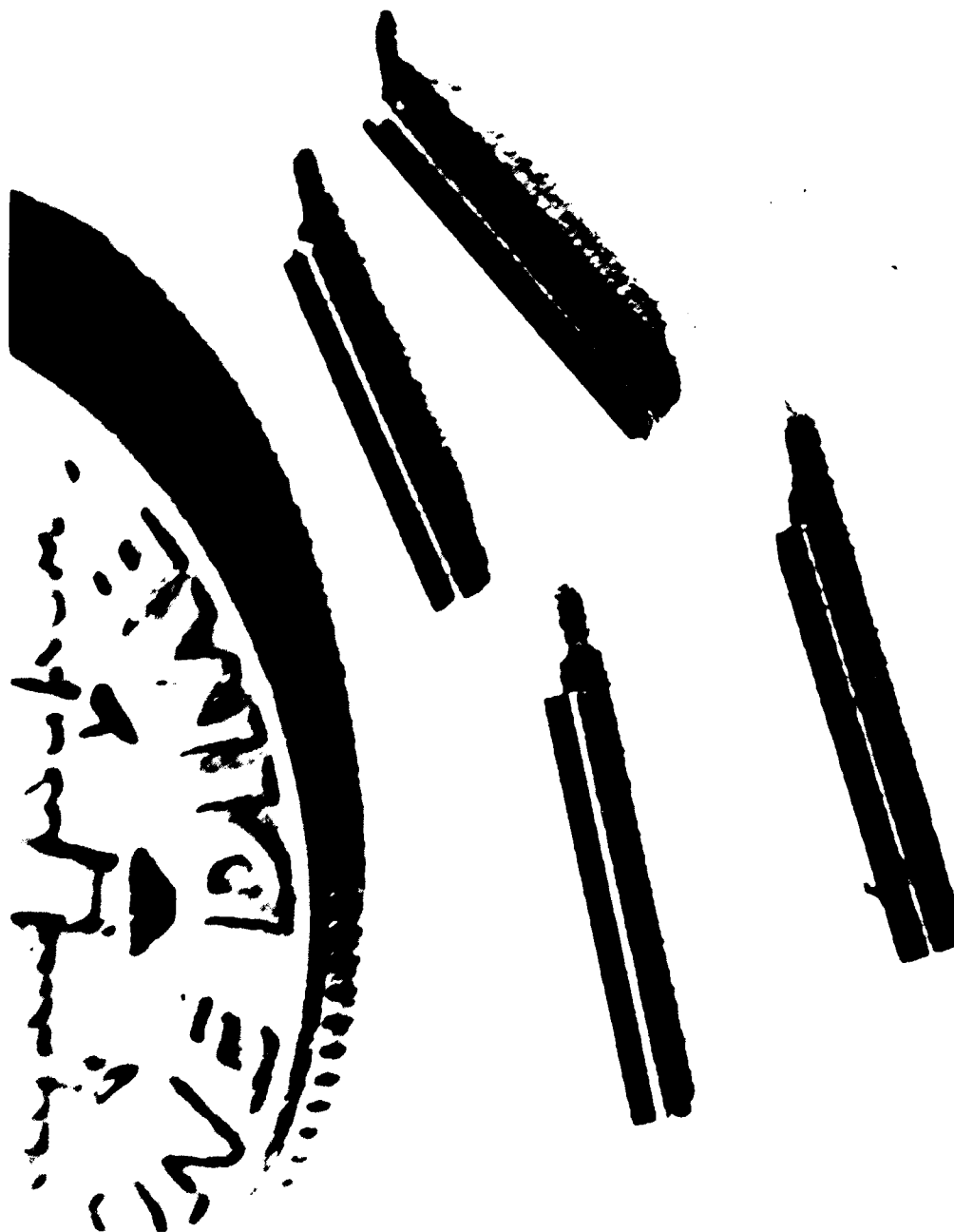
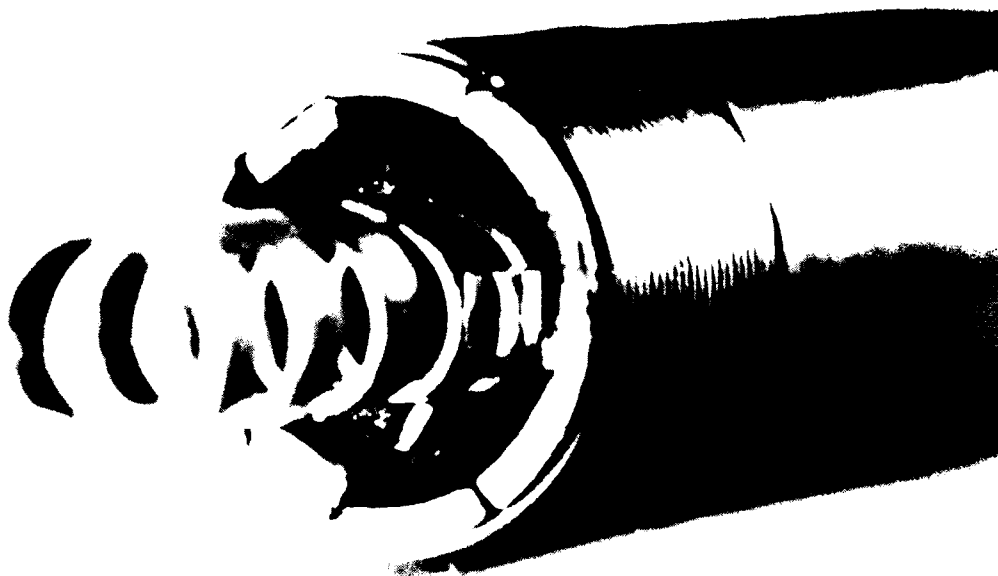


Figure 17. Diamond Helix Supports.

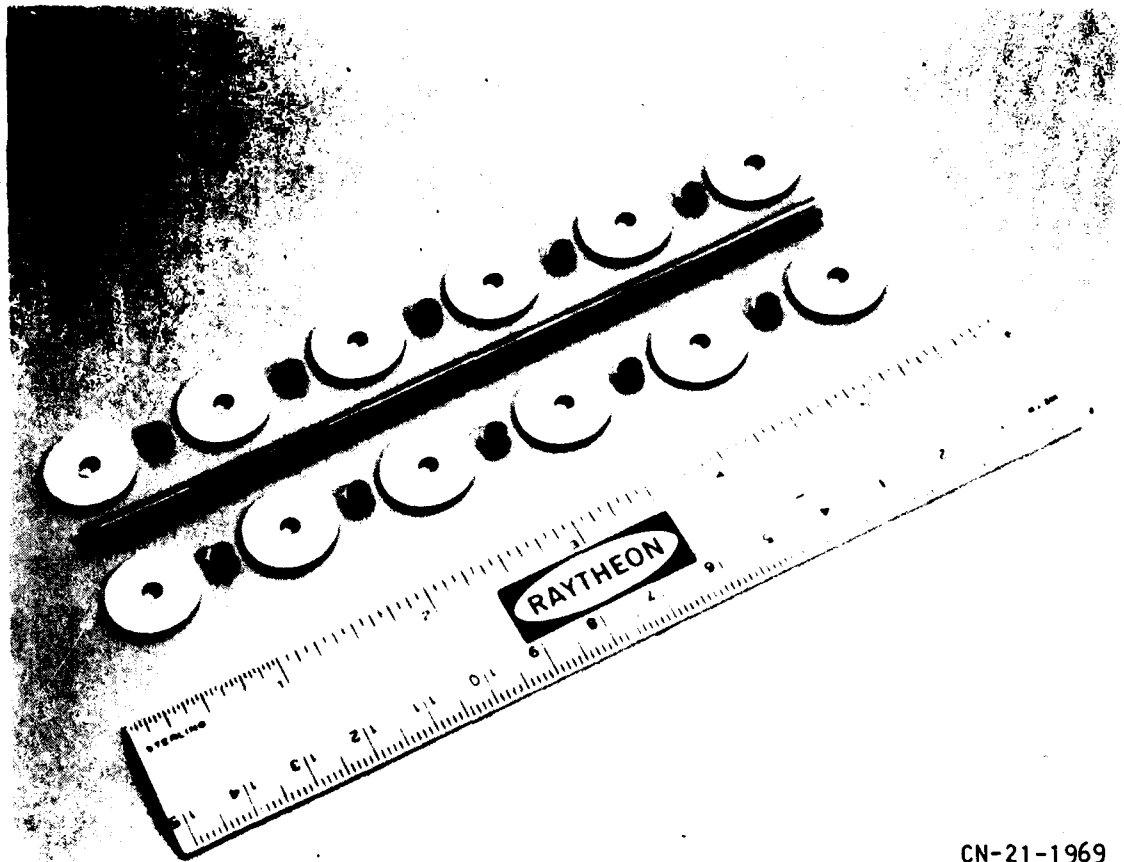
PT-5413



CN-21-1788

Figure 18. Wire Wrapped Helix Assembly.

PT-5413



CN-21-1969

Figure 19. Circuit Assembly Parts.



Figure 20. Circuit Assembly.

Two methods for removing the heat from the circuit assembly were tested by building two helix thermal test assemblies with different cooling arrangements. The first assembly was cooled in the conventional way by a heat sink clamped onto the outer diameter of the PPM focusing structure. This is shown schematically in Figure 21. The second assembly was cooled by liquid flowing through small pipes imbedded between the poles of the PPM structure as shown in Figures 22 and 23. This second design eliminates the temperature difference due to the iron poles, but it requires spreading of the magnet halves by enough to clear the cooling pipes with some resultant degradation of the magnetic focusing field strength. The choice between these two possible design approaches may, in a particular TWT design, be dictated by magnetic focusing field requirements rather than thermal (heat flow) considerations. Hence, the reason for evaluating both methods of cooling a PPM focused helix TWT.

The helix assembly shown in Figure 18 is brazed inside the PPM pole assembly so that the heat flows outward from the wire wrapped shell to the PPM poles and spacers. The thermal test helix assemblies were made with one end of the helix brazed to a ridge waveguide transition and the other end brazed to a coaxial feed so that current could be fed in to heat the helix in the same manner as in the previous thermal test assemblies. There were 21 helix turns between the two connections. Figures 24 and 25 show the thermal test helix assembly with external heat sink blocks which are water cooled. The photographs show the center pipes, thermocouple connections, cooling blocks, and the threaded stud to which the AC current lead is connected. Figures 26 and 27 show the thermal test assembly with cross flow fluid cooling pipes. The photographs show the inlet and outlet water pipes and manifolds (between which the cooling pipes connect). Also shown are the thermocouple connections, PPM poles, ridge waveguide output, and the threaded stud to which the AC current lead is connected.

3.2.3 Thermal Test Results - PPM Focused Assemblies

The two PPM focused helix assemblies were given the usual thermal test by passing AC current through the helix with the entire assembly inside a vacuum bell jar. Cooling water was circulated through the cooling passages

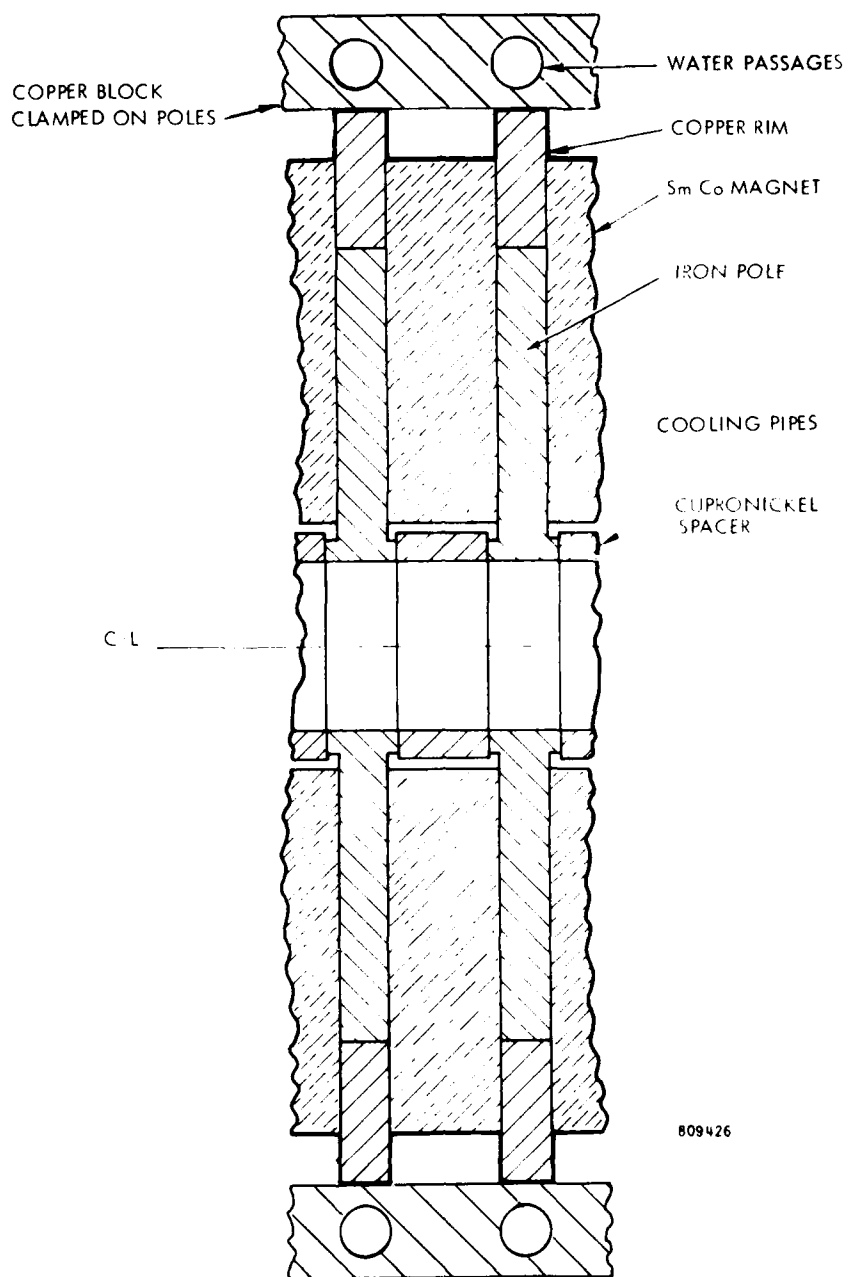


Figure 21. PPM Cell With Copper Rims Showing External Copper Cooling Blocks.

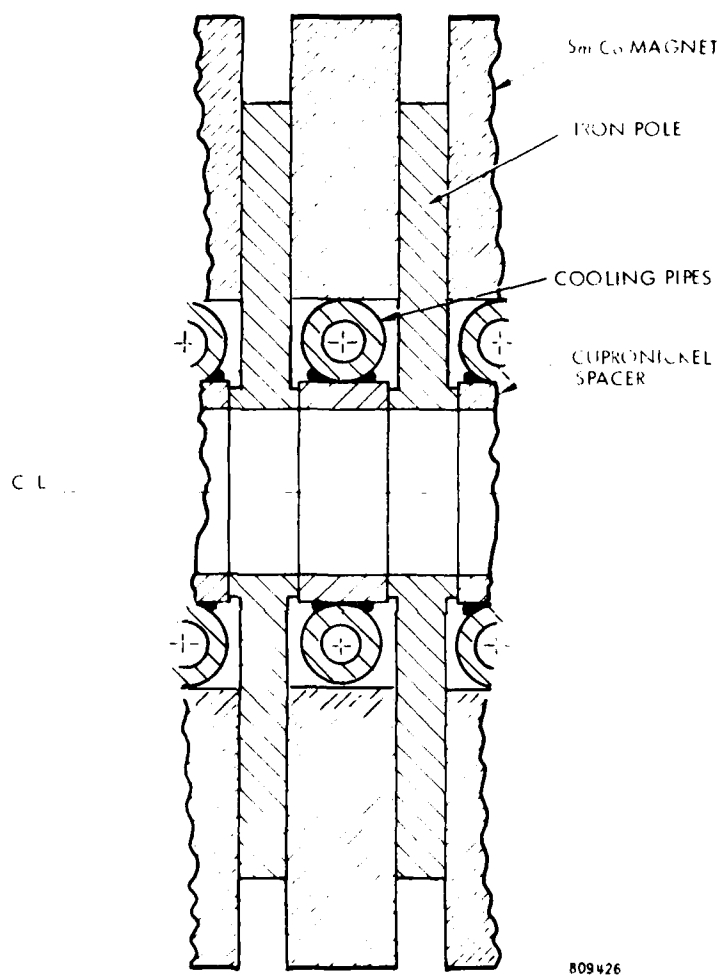


Figure 22. PPM Cell Showing Imbedded Cooling Pipes.

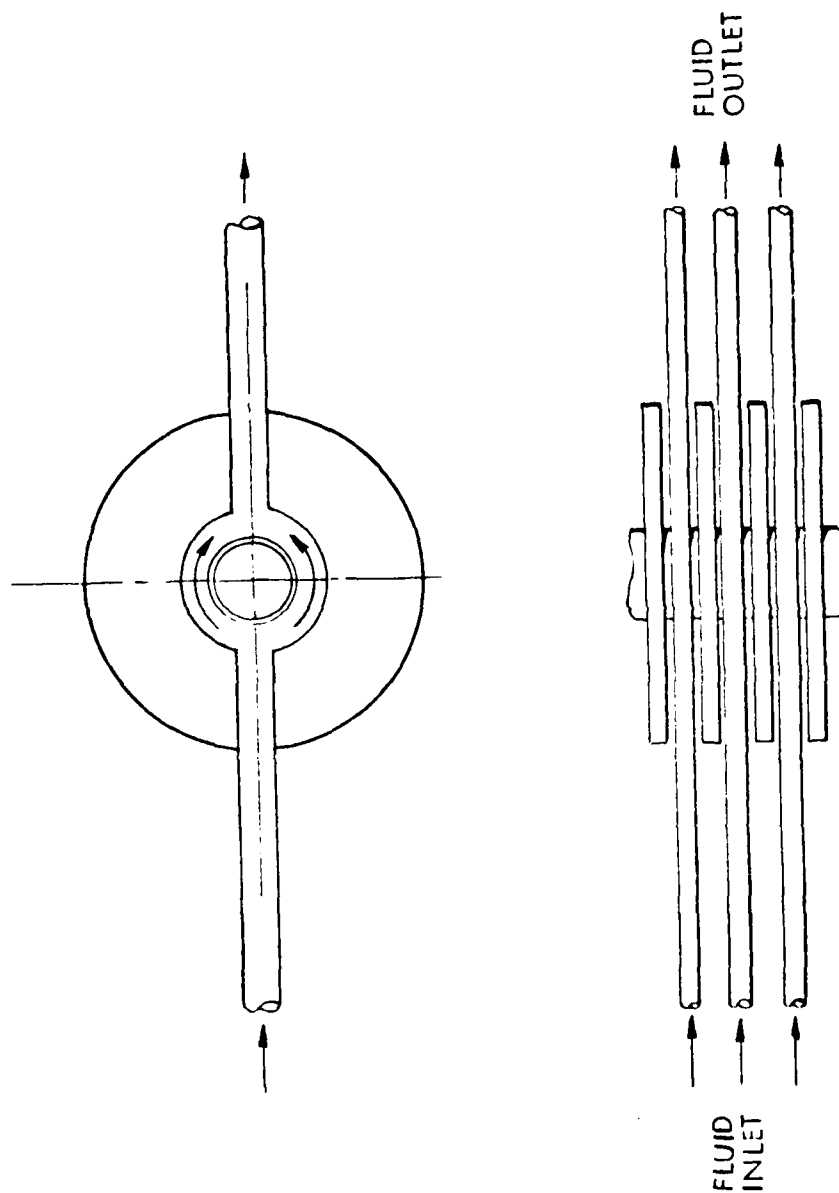
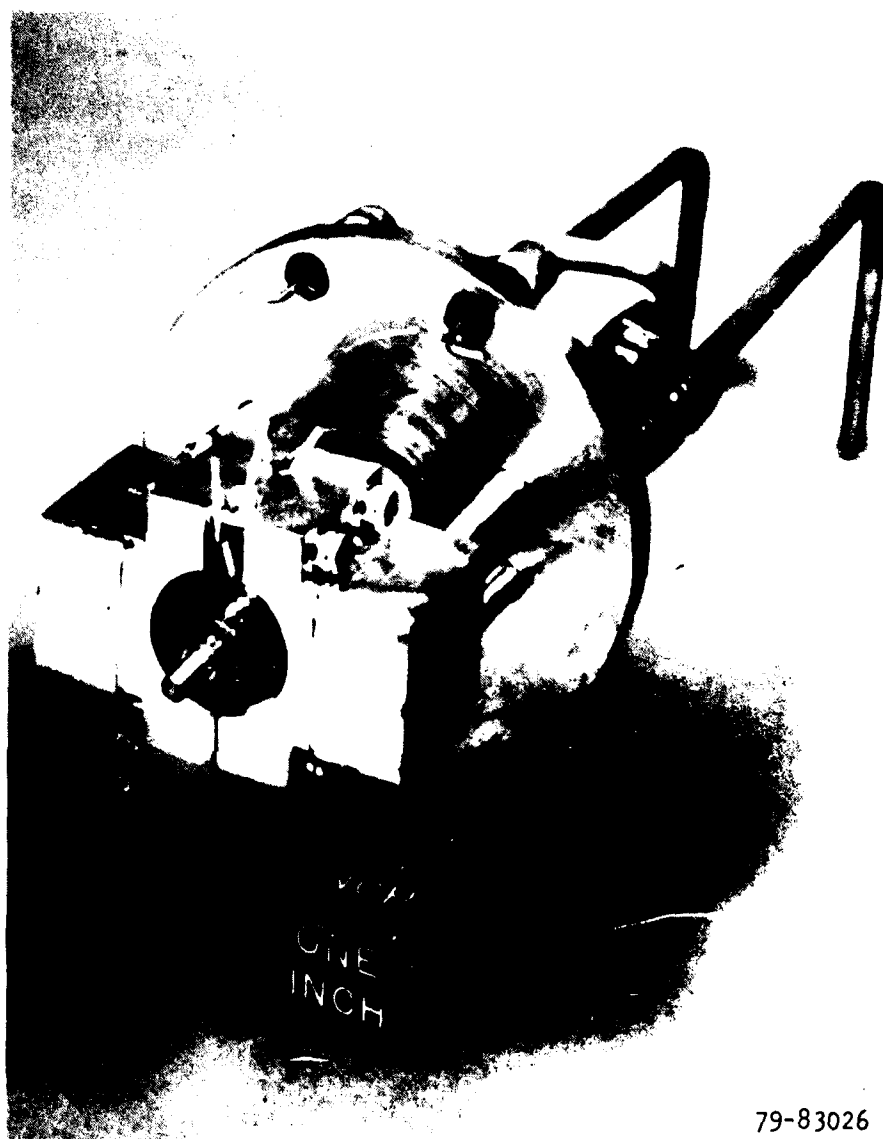


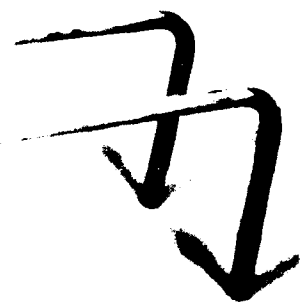
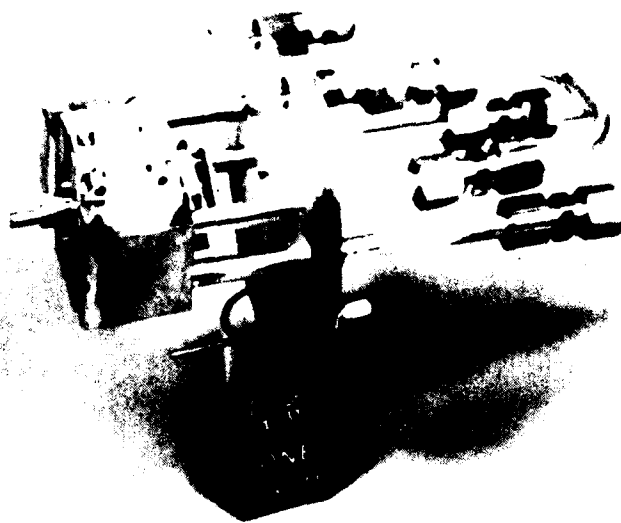
Figure 23. PPM Structure with Fluid Cooling.



79-83026

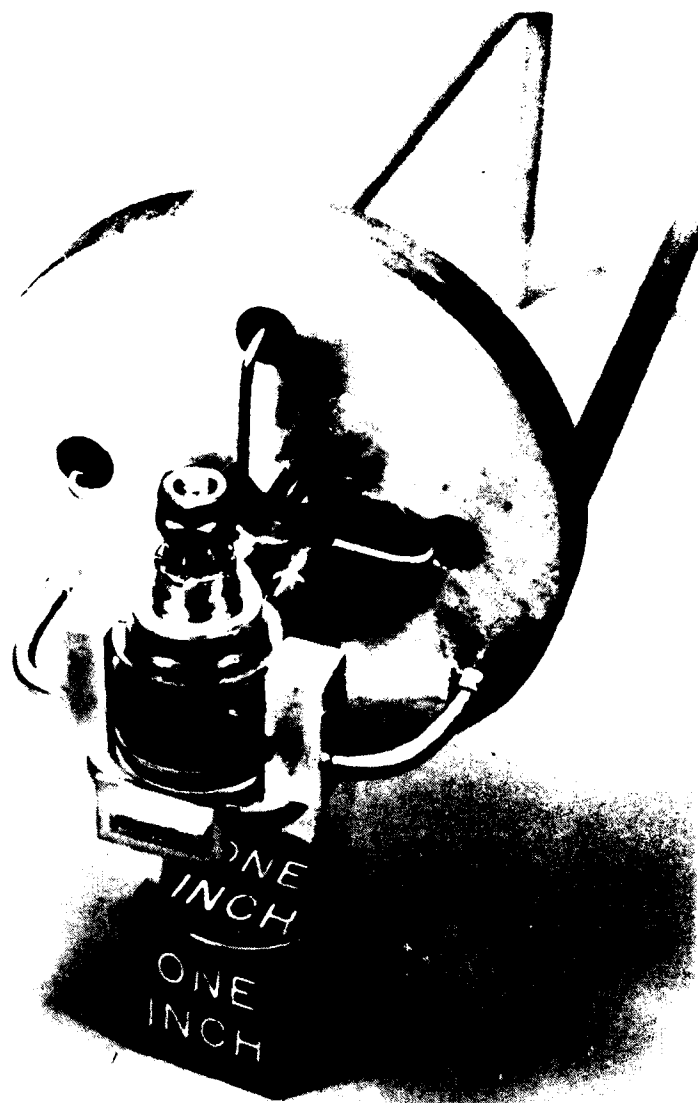
Figure 24. Thermal Test Assembly with External Heat Sink.

PT-5413



79-83028

Figure 25. Thermal Test Assembly with External Heat Sink.



79-83025

Figure 26. Thermal Test Assembly with Cross Flow Fluid Cooling Pipes.

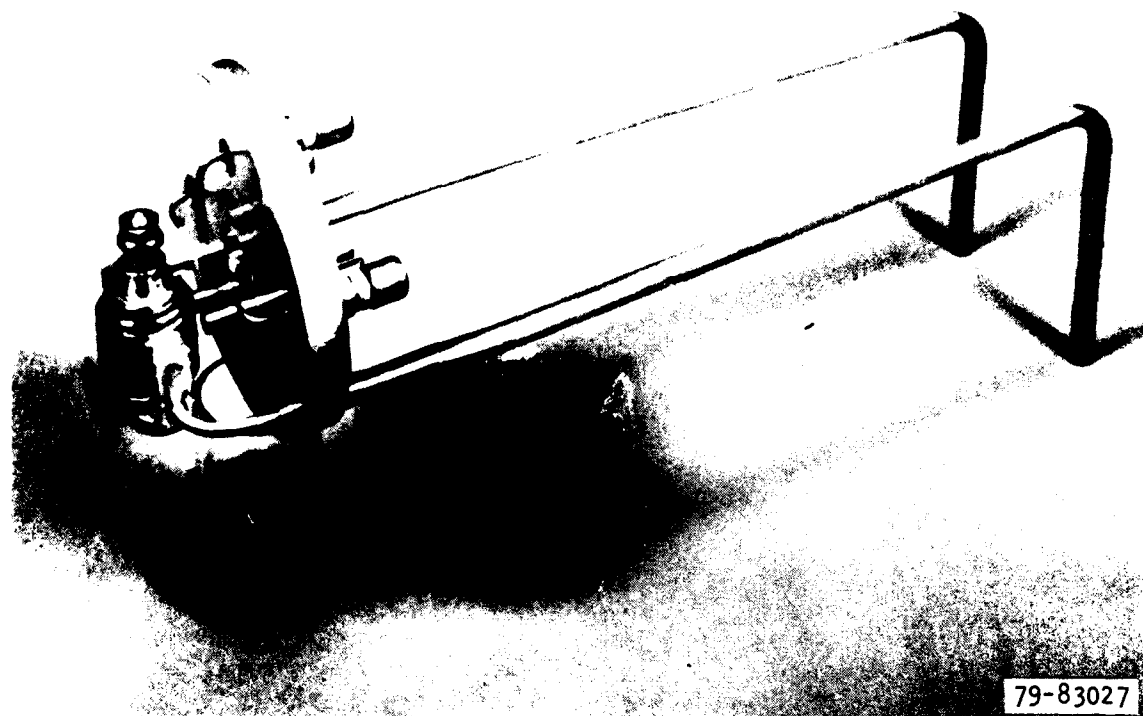


Figure 27. Thermal Test Assembly with Cross Flow Fluid Cooling Pipes.

to furnish the required heat sink. Also, test results on a helix of the same dimensions supported by diamonds under compression within a water cooled copper shell are shown for comparison. The theoretical temperature rise also has been calculated for each of these three structures for comparison with the measured values.

Figure 28 shows the measured and calculated average helix temperature rise for the basic diamond supported helix assembly with water cooled copper shell. This is a relatively simple structure to build and the calculated and experimental values of helix temperature rise agree very well. This shows that the helix compression has been properly controlled so that the interfaces have the expected thermal resistance.

Figure 29 shows the temperature rise in a diamond supported helix assembly brazed within a conventional PPM focusing structure which has cooling blocks clamped onto the outer diameter of the poles. The measured and calculated average helix temperature rise are plotted. The measured helix temperature is about 40% higher than the calculated value indicating extra temperature drop somewhere. This assembly also was equipped with a thermocouple to measure the temperature at the outer diameter of the cupronickel spacers between the poles. This gives the temperature difference across the poles including the interface between the outer diameter of the poles and the cooling blocks. This temperature agrees very well with the calculated value. Inspection of the assembly indicated incomplete flow of solder into the joint between the wire wrapped helix assembly outer diameter and the inner diameter of the pole-spacer assembly so that this interface junction thermal resistance probably was higher than desired. Even so, this helix assembly can dissipate 300 watts per inch at a helix temperature rise of 418°C . The assembly was put through a number of thermal cycles without any problems. It was shipped to NRL still intact.

Figure 30 shows the temperature rise in a diamond supported helix assembly with built-in cross flow cooling pipes brazed to the outer diameter

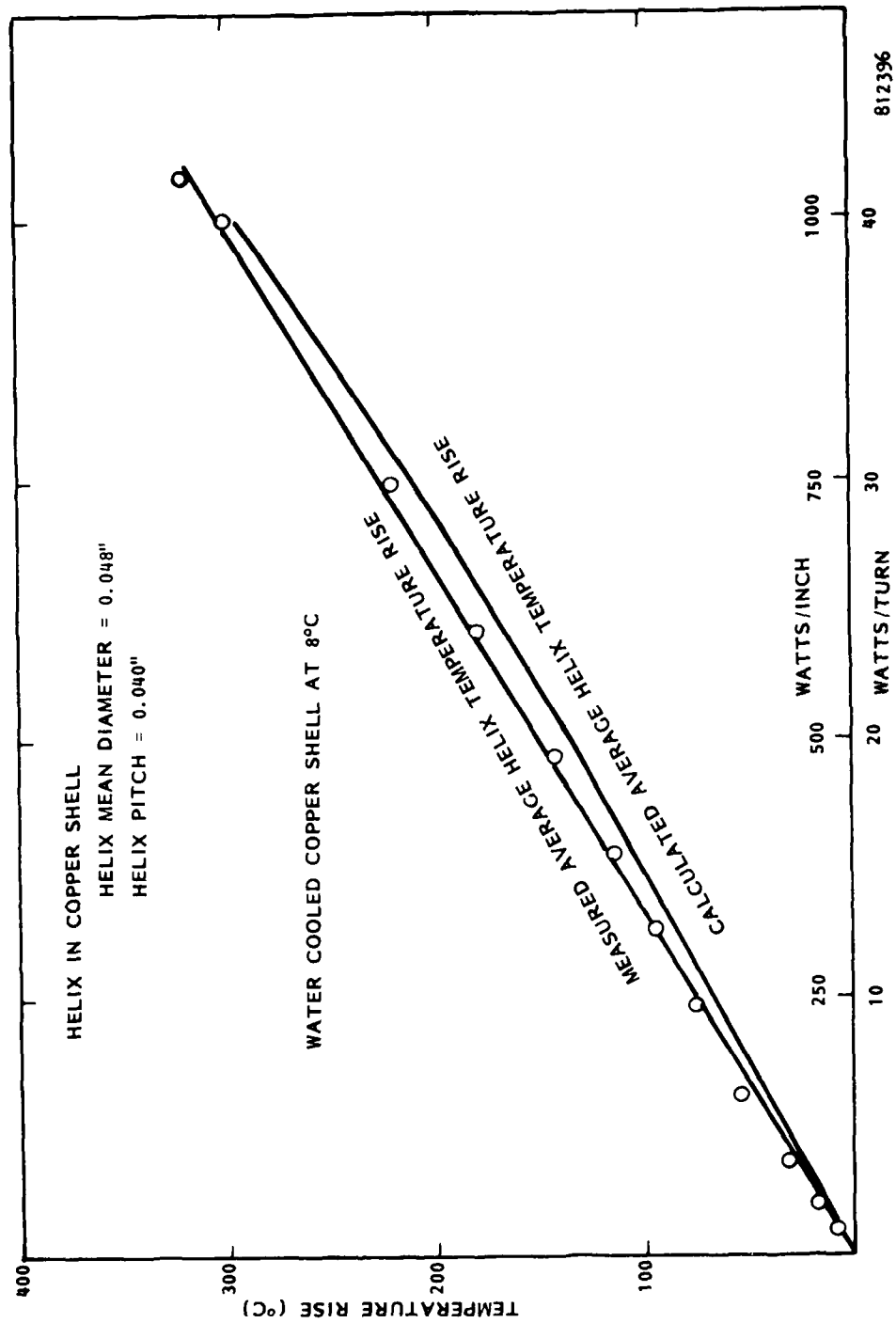


Figure 28. Thermal Test Assembly No. 2A.

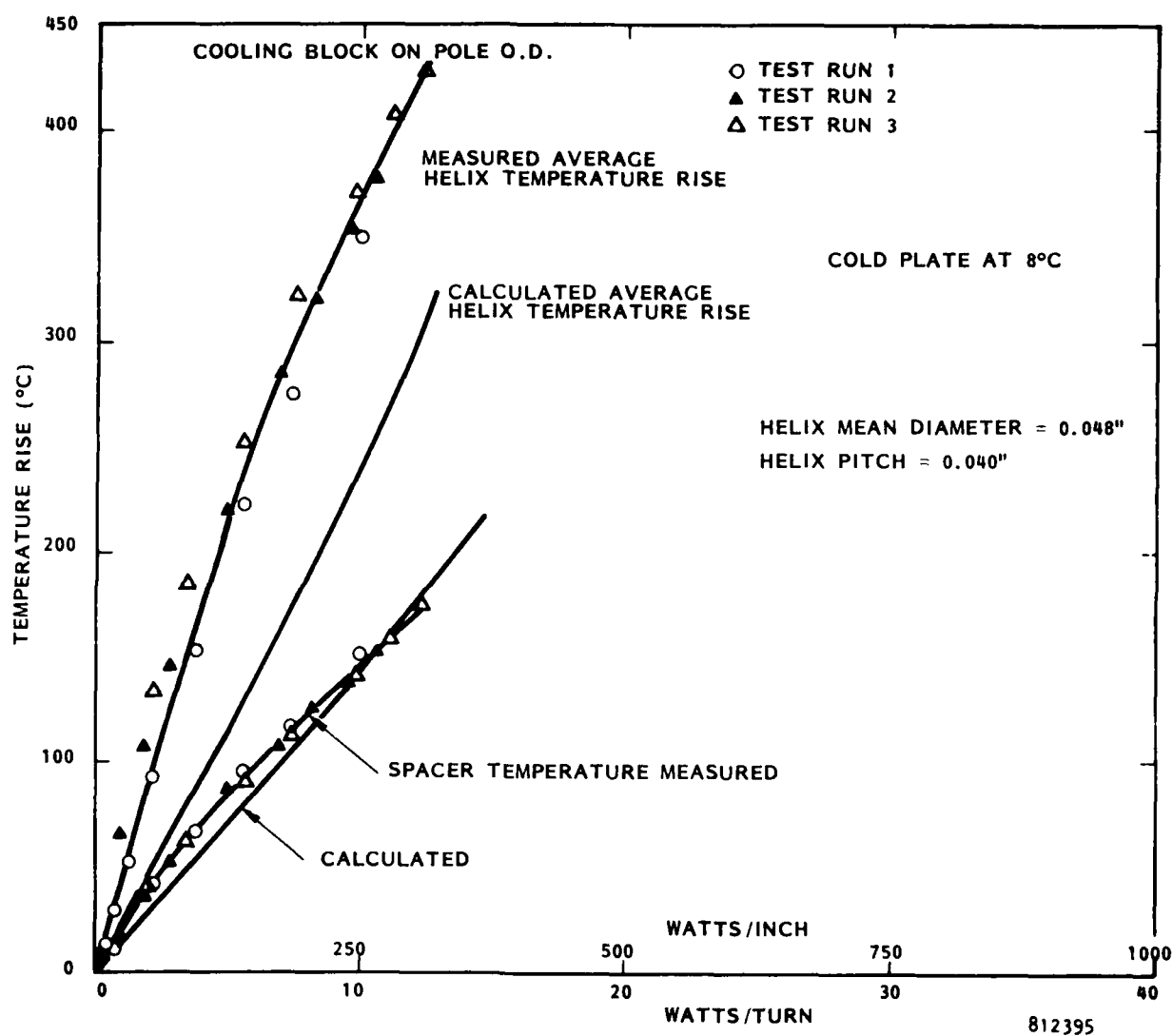


Figure 29. Thermal Test Assembly No. II-1.

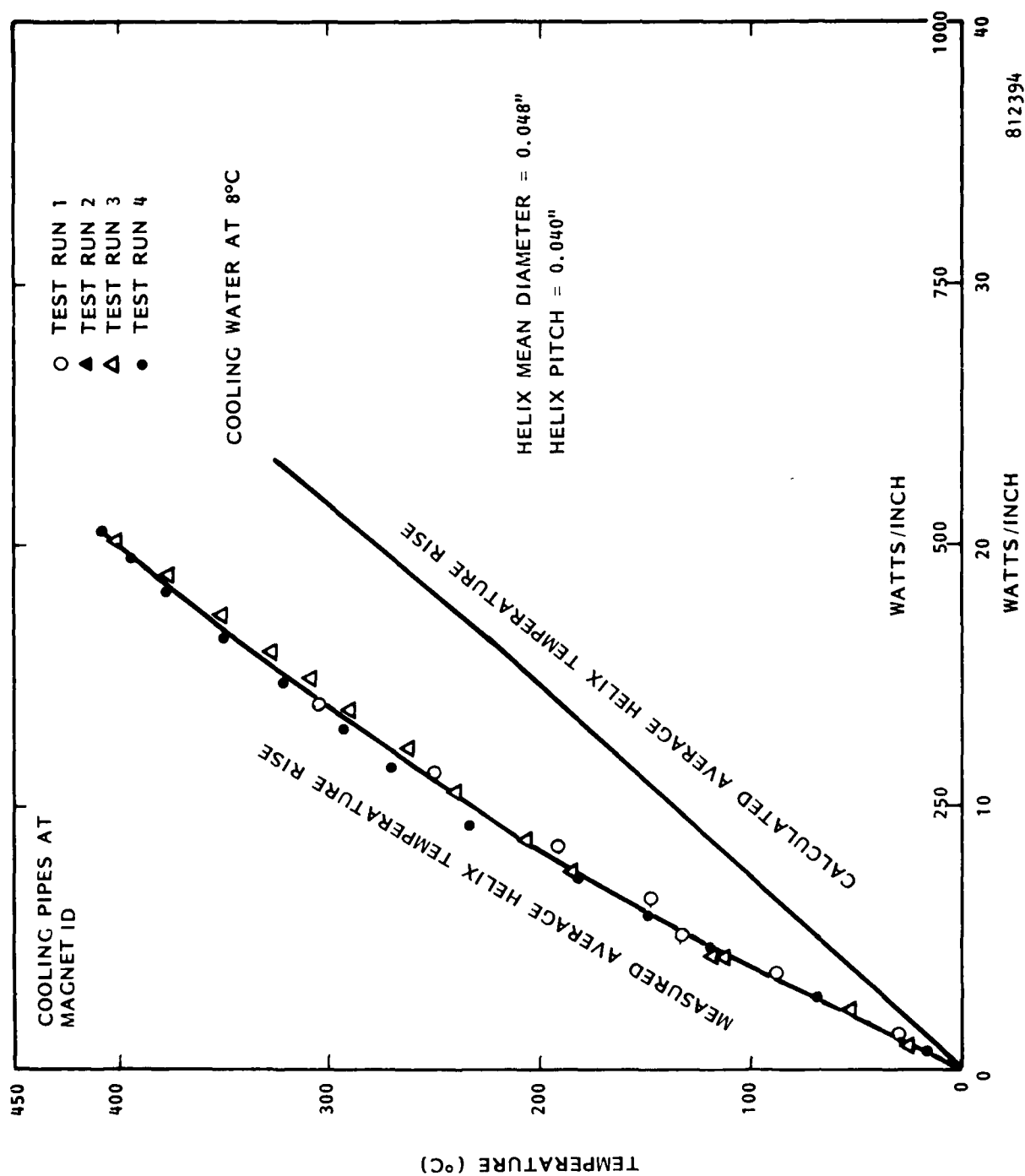


Figure 30. Thermal Test Assembly No. II-2.

of the spacers of the PPM structure. This construction eliminates the temperature difference across the PPM poles so that the helix temperature rise is less. The difference between the measured and the calculated helix temperature is about the same as in the preceding assembly. This helix assembly can dissipate 515 watts per inch at a helix temperature rise of 407°C . This is quite a respectable power dissipation capability for a K-band helix.

3.2.4 Conclusions

These tests have shown that a diamond supported compression helix assembly within a PPM focusing structure has good power dissipation capability. The measured temperature rise agreed well with the calculated temperature rise, thus verifying the analysis method and also showing that the construction method gives the desired predicted performance. The wire wrap method is ideally suited for diamond supported helices at K-band and higher frequencies because it gives well-controlled pressure at all of the helix to support interfaces even when dimensional variations occur. Thus, it is practical to achieve consistent thermal interfaces with the tolerances which can be obtained in practical structures. The use of "heat shrink" or other methods of forcing or "stuffing" a helix and support rods into a shell assembly was considered and rejected early in this work because of the impractical tolerances which must be maintained to achieve the necessary minimum pressure at the interfaces. The wire wrap method, in which the wrapping wire is maintained at a pre-established tension, was chosen because of the consistent interface pressures which are achieved. These test results verify the validity of the choice of the wire wrap assembly method.

The power dissipation which was measured of 515 watts per inch at 407°C helix temperature would make it possible to build a PPM focused K-band TWT with up to 500 watts average output power (depending on the beam transmission) if there is provision for cooling by heat risers or cooling pipes placed between the PPM poles. With cooling at the outer diameter of the PPM poles the measured power dissipation was 300 watts per inch at 418°C , which would predict an attainable average power output of 300 watts in a PPM focused K-band TWT.

3.3 RF Properties

The rf properties at microwave frequencies of diamond have not been extensively studied. The published values quoted in Sections 3.2 and 3.3 of Appendix A indicate that it has about the same dielectric constant (5.5 at low and high frequencies) and that it should be low loss because of its extremely high resistivity ($>10^{16}$ ohm cm). Test results on diamond supported helix assemblies confirm these statements.

The measured helix velocity and impedance on several different helix assemblies have agreed with the values computed using the published dielectric constant. A typical set of measurements is shown in Figure 31 compared with calculated phase velocity assuming a dielectric constant of 5.58.

The measured loss of diamond supported helix assemblies has been equal to or lower than conventional helix assemblies. This is shown in Figure 32 where helix loss measurements in a number of TWT helices are compared by plotting the loss per wavelength on helix versus frequency. The boxes for boron nitride and beryllia supported helices enclose the data points obtained on a number of transparent TWT's for which loss measurements were recorded for each tube built. The K-band diamond supported helix loss measurements were made on the copper plated tungsten helix structures described in this report. The copper diamond supported helix measurements were made at a 2500 watt cw power level on an experimental brazed copper helix supported by diamonds. This is a true high power insertion loss measurement obtained by measuring power in, power out, and power (heat) dissipated in this helix assembly. These results were described in detail in (14) and partially in (15,16,).

The coupling of rf power from the helix to an output waveguide must be done by some means which does not degrade the power handling capability of the helix. Conventional coaxial line output structures have considerably less power handling capability than a diamond supported helix. The preferred output

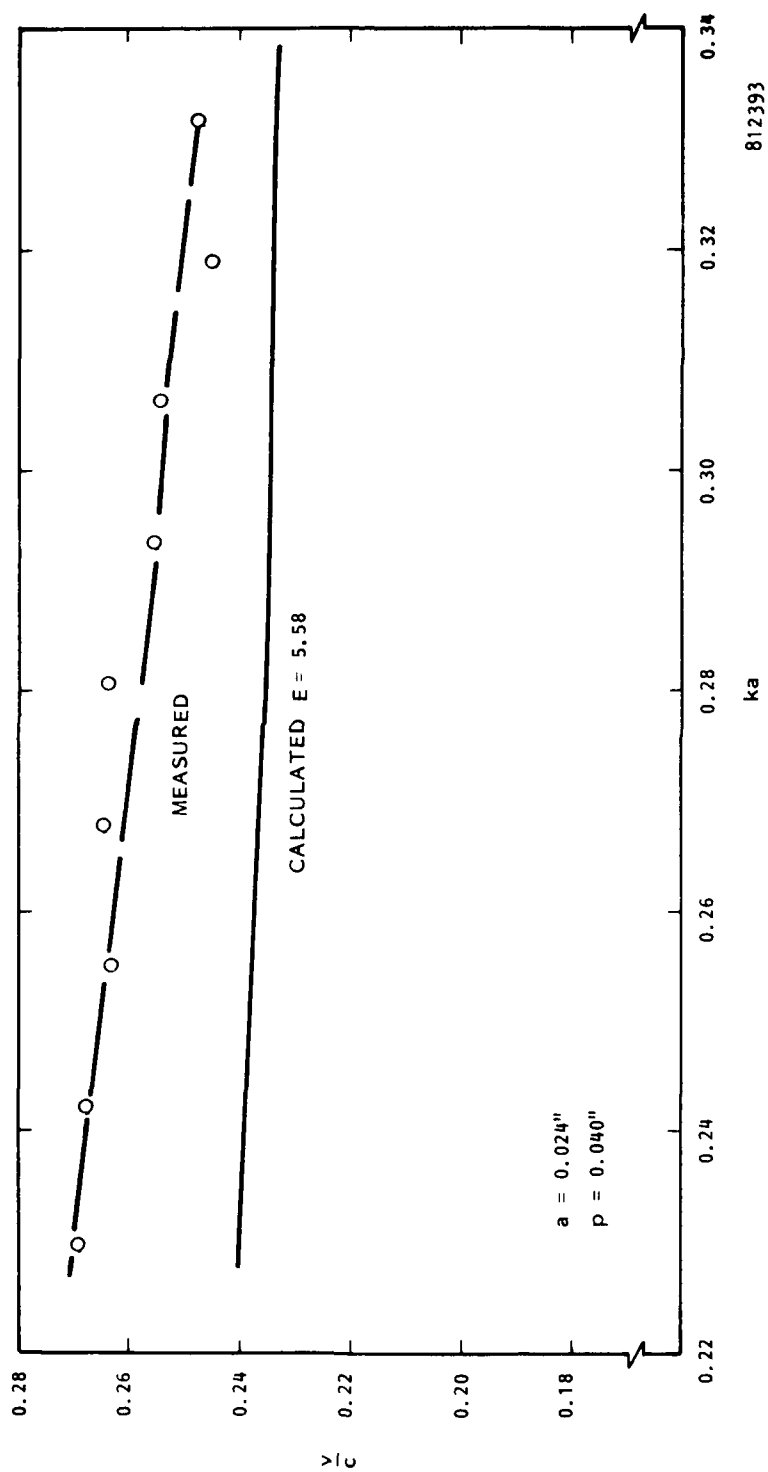


Figure 31. Diamond Supported Helix Phase Velocity.

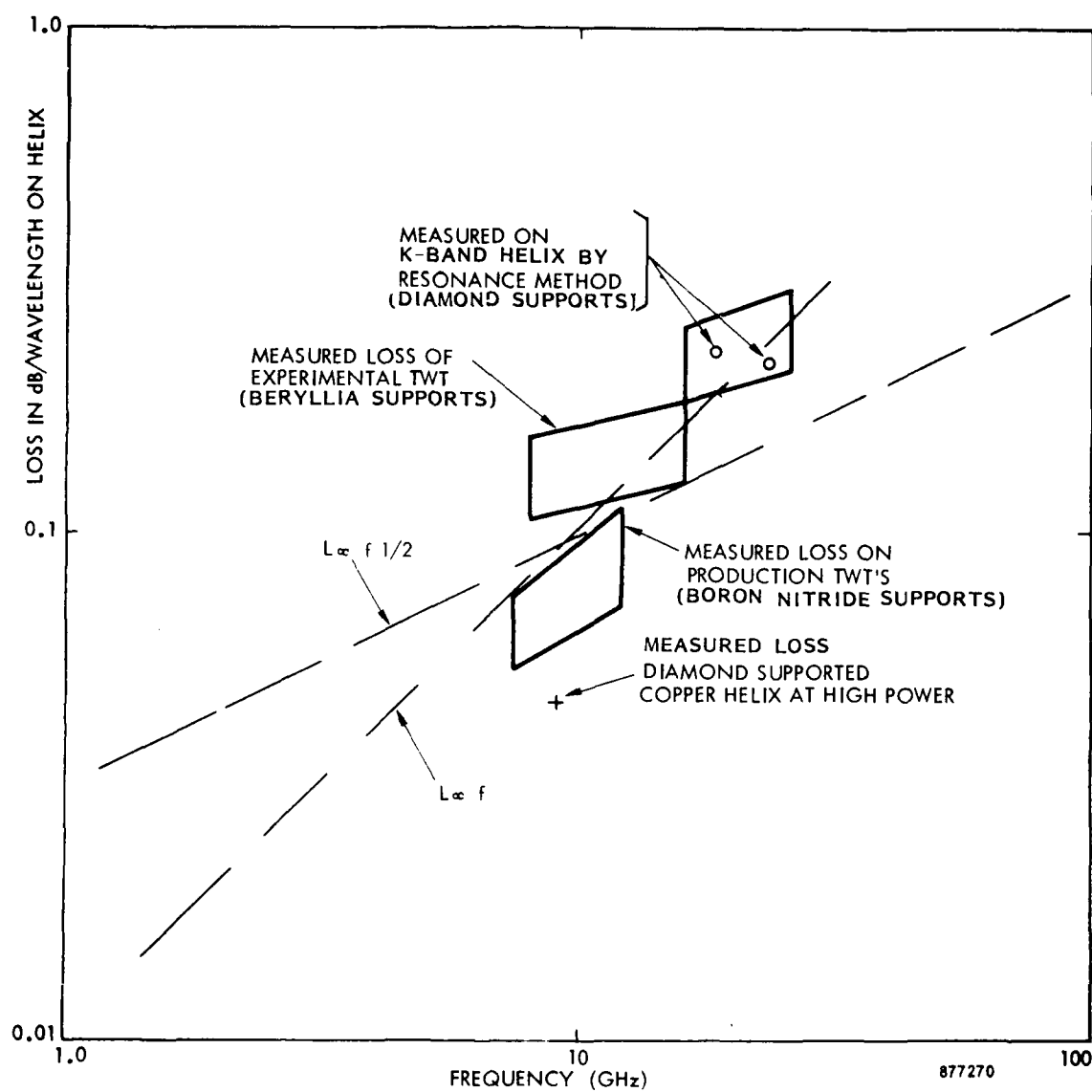


Figure 32. Summary of Measured Helix Loss At Frequencies Above I-Band.

coupling consists of a direct transition from the helix to waveguide with a ceramic window in the waveguide. A typical output coupler as used in a PPM focused diamond supported helix TWT is shown in Figure 33. The helix is directly brazed to a matching ramp in reduced height ridge waveguide, which then tapers to standard rectangular waveguide dimensions. A conventional poker chip ceramic window is in the rectangular waveguide section. The rf match obtained with this arrangement is good as shown by a typical measurement across the full waveguide band of a complete TWT helix assembly, output transition, and output window in Figure 34.

In general, diamond has microwave properties suitable for use as TWT helix supports. The dielectric constant is 5.50 to 5.58 and the loss factor is equal to or better than any other helix support material.

883680

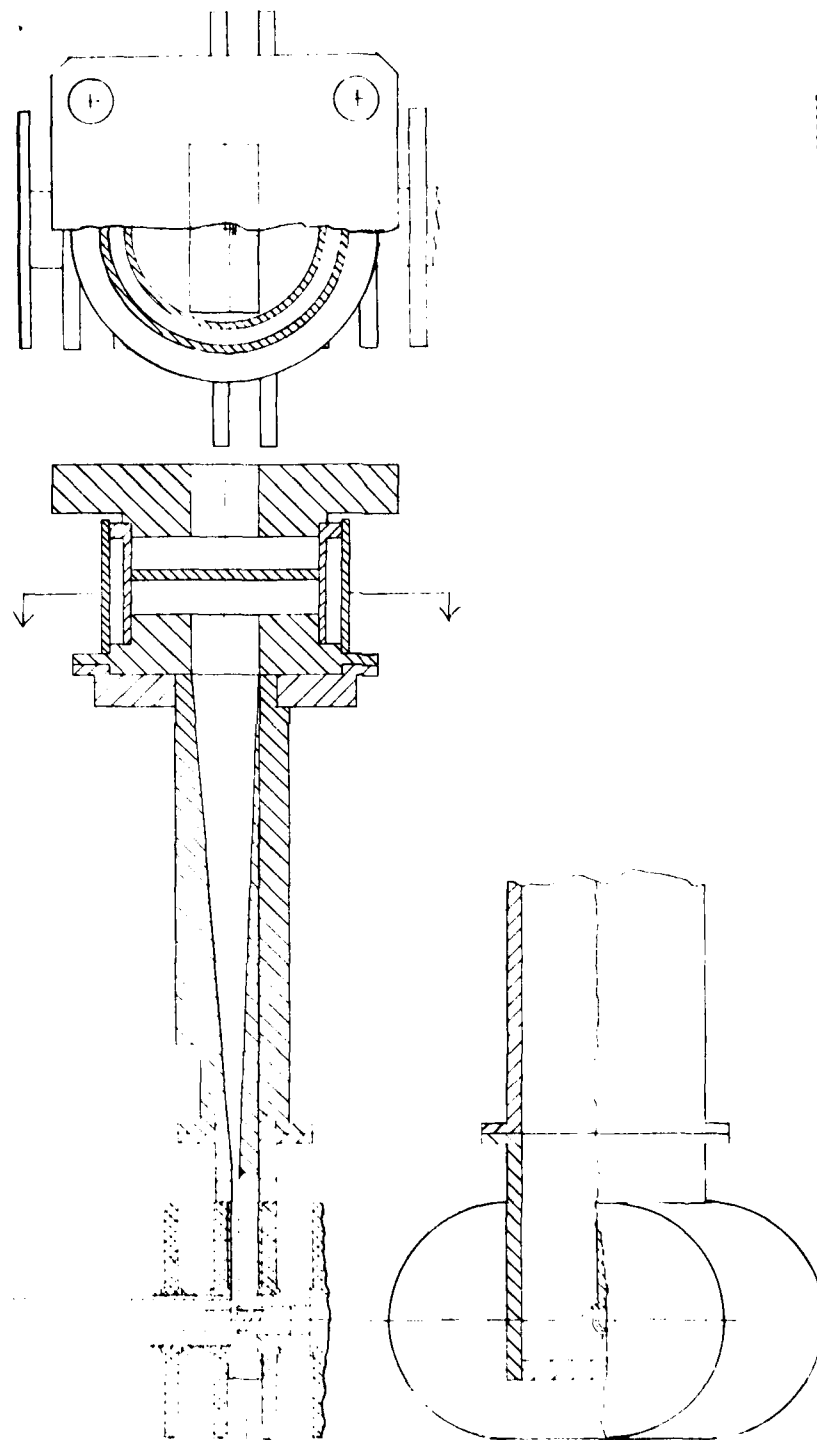


Figure 33. Output Coupler Layout.

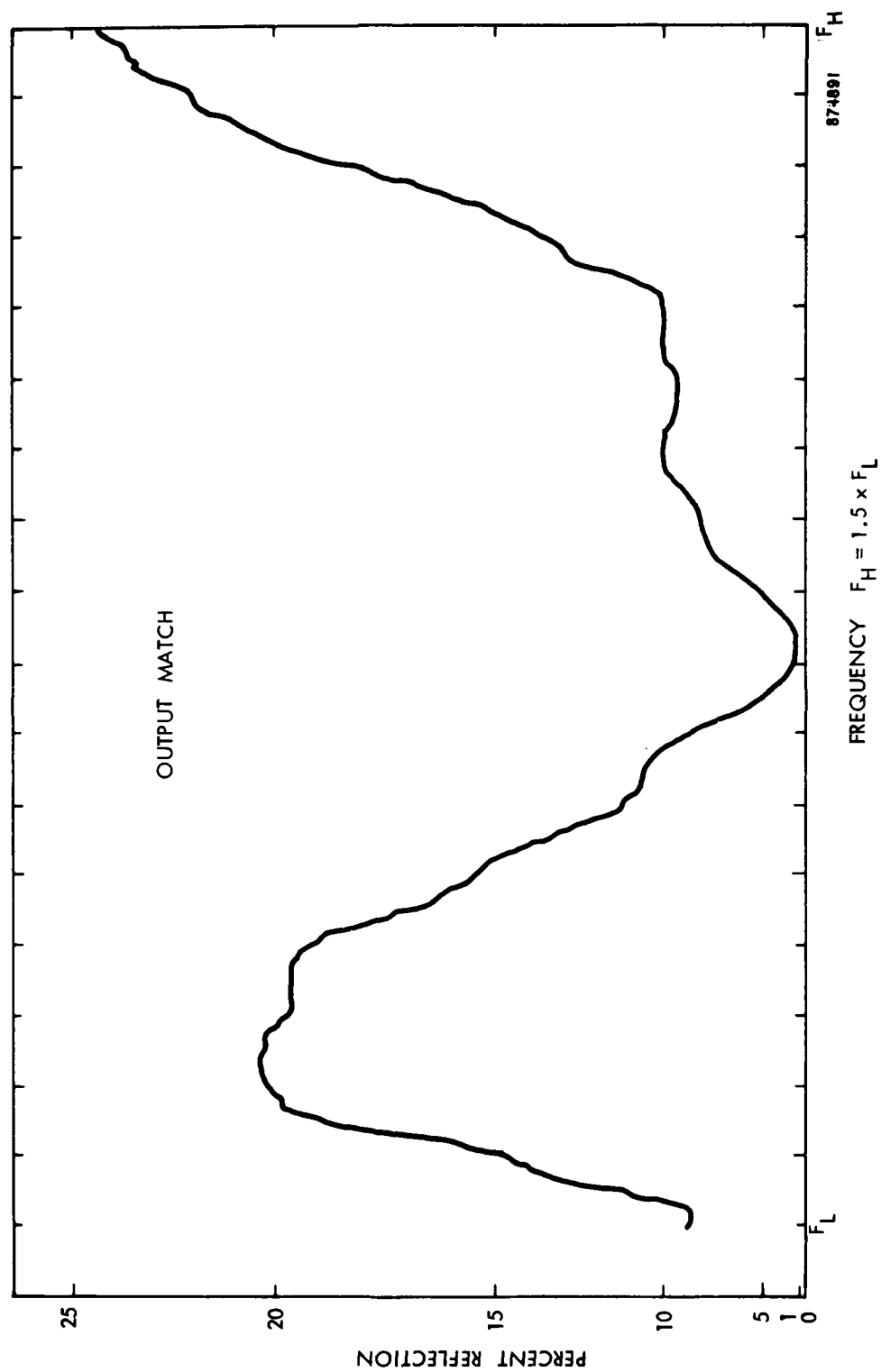


Figure 34. Output Coupler Match.

4.0 DELIVERIES

At the conclusion of the work in this contract the two PPM focused thermal test assemblies were delivered to NRL in fulfillment of the hardware requirements of this contract.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Natural diamond is recommended as an excellent helix support material when higher average output power is required than can be achieved by use of conventional dielectrics. Specific diamond supported helix designs for I, J, and K band were built and tested in this program. Power dissipation capability up to 1800 watts per inch in I-band and 1000 watts per inch in K-band were measured in diamond supported helix structures for use in solenoid focused TWT's. K-band diamond supported helix assemblies for PPM focused TWT's were tested at up to 500 watts per inch power dissipation. These results indicate that average output power of over 500 watts solenoid focused and 250 watts PPM focused should be practical in K-band. By extrapolation we can predict that 100 watts average output should be practical at 40 GHz in a PPM focused helix TWT and 200 watts in a solenoid focused tube.

Several construction techniques were examined and tested. The most practical one was shown to be the use of a copper plated tungsten helix held in compression by diamond support bars.

A simple analysis procedure was developed using thermal resistance elements for use in accurately calculating the temperature rise of a TWT helix for given power dissipation. Correlation of calculated values with experimental values was good, and this calculation method is recommended for practical engineering design.

The price and availability of natural diamond in sizes and shapes suitable for helix supports indicate that it should be most useful in the general frequency range of 10 to 50 GHz. There is a distinct possibility that man-made diamond-like materials may become available in the future for use as TWT helix supports. Further expansion of the use of diamond helix supports is recommended.

In particular, the development of 100 watt cw TWT's PPM focused with diamond helix supports to cover the frequency band of 18 to 40 GHz is feasible and should be undertaken.

APPENDIX A

Properties of Diamond*

1.0 GENERAL PHYSICAL PROPERTIES

1.1 Chemical Composition

1. Single Element Carbon

2. Major Impurities

Nitrogen Up to 0.25% (see types I and IIA below)

Nickel Up to 10% in synthetic diamond
1 PPM or less in natural diamond

Aluminum Up to 20 PPM in natural diamond
(see type IIB below)

Other Generally <10 PPM

3. Natural Diamond - Classifications by General Properties

Type I Nitrogen in percentages of 0.05% to 0.25%.

These are further subdivided into:

Type IA In which nitrogen is present as platelets in the crystal lattice.

Type IB In which nitrogen is present in substitutional positions in the crystal lattice.

*Abstracted from reference 17 with additions in some sections.

Type II

No nitrogen is present. These are further subdivided into:

Type IIA

The purest form of diamond with less than 0.02% nitrogen and excellent electrical insulating properties (resistivity of 10^8 to 10^{17} ohm-cm). This is the kind generally called heat sink grade.

Type IIB

Is a semiconductor due to either aluminum or boron impurity. The resistivity is about 1 ohm-cm.

Ref. 1. E.C. Lightowers, Science and Technology of Industrial Diamonds, Vol. 1, Ed. J. Burls, Industrial Diamond Information Bureau, 1967.

2. M. Seal - discussion on diamond properties.

1.2 Density

Value:

Average of 35 diamonds	$3.51524 \text{ g cm}^{-3}$
(25°C) Spread	$0.00077 \text{ g cm}^{-3}$
Average of 14 type II	$2.51506 \text{ g cm}^{-3}$
Average of 19 type I	$3.51537 \text{ g cm}^{-3}$

Ref 2. R. Mykolajewycz, J. Kalnajs and A. Smakula, J. Applied Physics, 35, 1773, 1964.

The usual industry practice is to specify diamond size in carats. One carat equals 200 milligrams.

1.3 Chemical Reactions

Diamond is extremely inert chemically and is not attacked by any known acid.

Diamond will react with residual oxygen in the system when heated in a vacuum system above 800°C. The reaction results in CO molecules on the surface which then react to form CO₂ gas and a carbon deposit on the surface of the diamond. This graphitization does not become noticeable until 1000°C in vacuum systems with pressures below 1×10^{-5} torr. Bulk graphitization (direct diamond to graphite transition) does not occur below about 1600°C.

The process tends to be self limiting and stops at a thickness which is determined by the temperature, e.g.:

1000°C	several hundred Angstroms
1200°C	somewhat thicker
1600°C	bulk graphitization begins

2.0 THERMAL PROPERTIES

2.1 Thermal Conductivity

1.	Value:	20°C	Type I	9 watts deg ⁻¹ cm ⁻¹
			Type IIA	26 watts deg ⁻¹ cm ⁻¹
2.	Maximum:	-190°C	Type I	24 watts deg ⁻¹ cm ⁻¹
			Type IIA	120 watts deg ⁻¹ cm ⁻¹

Ref. R. Berman, Physical Properties of Diamond, Ed. R. Berman, Claredon Press, 1965.

Figure A-1 compares the thermal conductivity of diamond with several commonly used materials in the temperature range of interest to TWT usage.

2.2 Thermal Expansion (Linear Coefficient)

Value:	20°C	$0.8 \pm 0.1 \times 10^{-6}$
	100°C	$0.4 \pm 0.1 \times 10^{-6}$
	100°C - 900°C	$1.5 - 4.8 \times 10^{-6}$

Comment: This is about the same as boron nitride. See Figure A-2.

Ref. J. Thewlis and A. R. Davey, Phil. Mag. 1, 409, 1956;

B. J. Skinner, Am. Min. 42, 39, 1957;

A. Goldsmith, T. E. Waterman, H. J. Hirschhorn; Handbook of Thermophysical Properties of Solid Materials, Vol. 1, Pergamon Press, 1961.

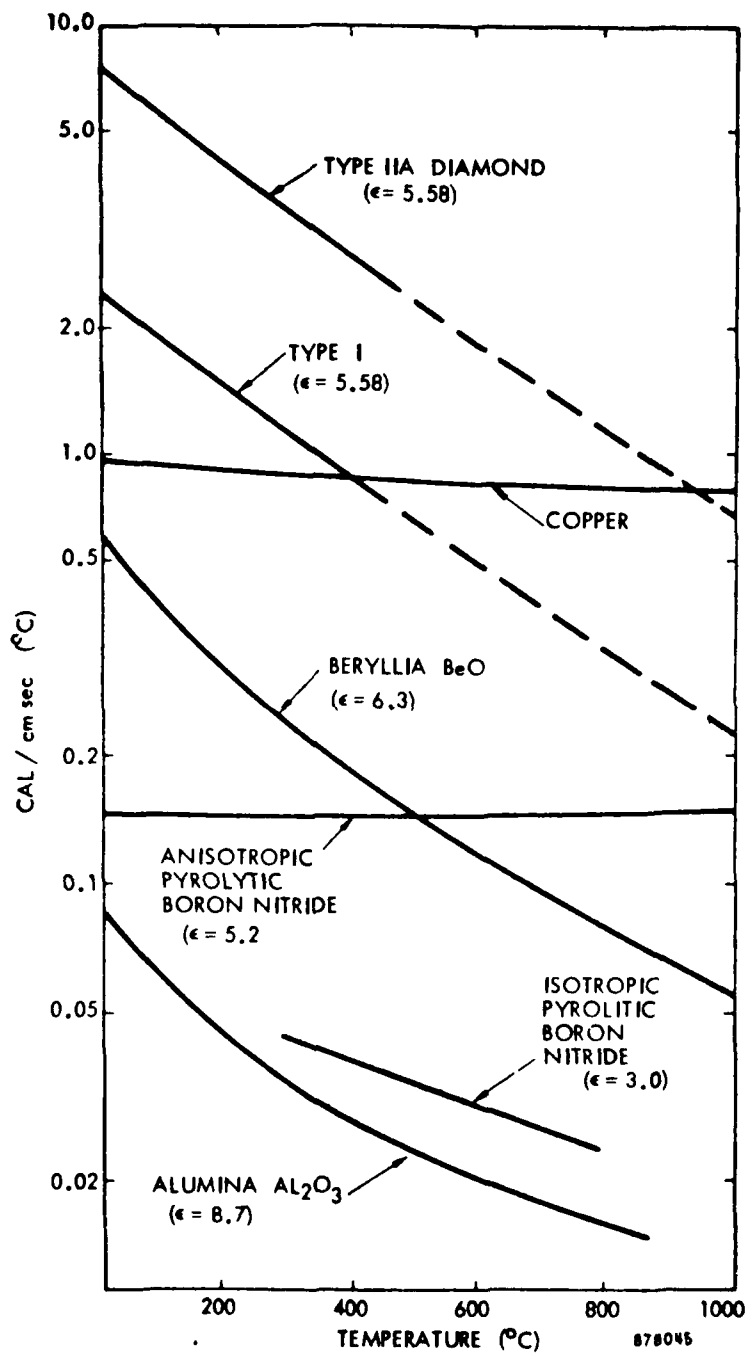


Figure A-1. Thermal Conductivity vs Temperature.

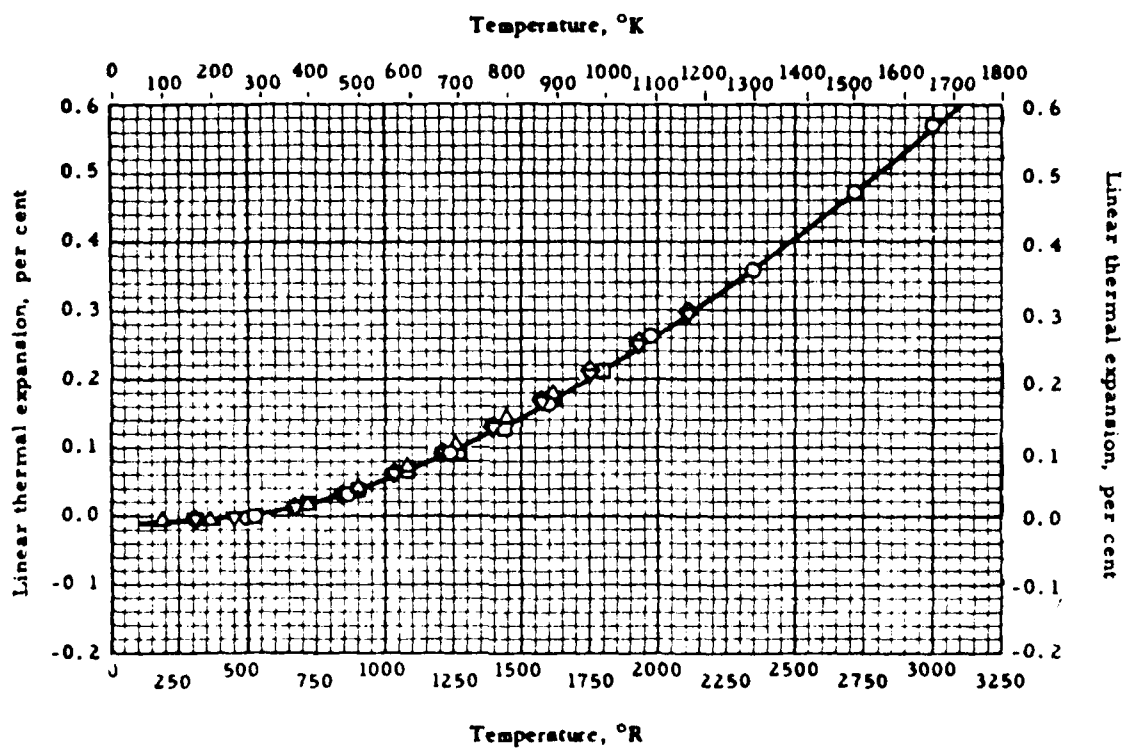


Figure A-2. Linear Thermal Expansion.

2.3 Specific Heat (Constant Volume C_v)

Value: 20°C 1.478 Cal G-atom⁻¹deg⁻¹

NOTE: Effective Debye Temperature 0 - 800°C

$$\theta_D = 1860 \pm 10^\circ\text{K}$$

Effective Debye Temperature 0°K

$$\theta_D = 2220 \pm 20^\circ\text{K}$$

Ref. D.L. Burk and S.A. Friedburg, Phys. Rev. 111, 1275, 1958;
J.E. Desnoyers and J.A. Morrison, Phil. Mag. 3, 42, 1958;
A.C. Victor, J. Chem. Phys. 36, 1903, 1962.

3.0 OPTICAL AND ELECTRICAL PROPERTIES

3.1 Refractive Index

Values:	At Hg green 5461 A	$\mu = 2.4237$
	At Ha red 6563A	$\mu = 2.4099$
	Near cut-off in ultra-violet at 2265 A	$\mu = 2.7151$

Ref. R. Peter, Z. Phys., 15, 358, 1923.

3.2 Dielectric Constant

Value:	5.58 \pm 0.03 at 27°C and 0 - 3 kHz
	5.5 at 300°K and 3×10^{12} Hz

Ref. S. Whitehead and W. Hacket, Proc. Phys. Soc., 51, 1753, 1939;
D.F. Gibbs and G.J. Hill, Phil. Mag. 9, 367, 1964;
M. Neuberger. Diamond, 1967.

NOTE: Diamond is a non-polar material; for all frequencies below the visible or ultra-violet absorption peak, the dielectric constant should be independent of frequency. This is verified by the above demonstrated adherence to Maxwell's relation between the dielectric constant ϵ and the index of refraction n ,

$$\epsilon = n^2$$

It also implies that microwave losses are extremely low, though no direct measurements of its loss tangent at microwave frequencies are known our tests on diamond supported helices have shown the loss to be extremely low.

AD-A081 928

RAYTHEON CO WALTHAM MASS MICROWAVE AND POWER TUBE DIV
DIAMOND TECHNOLOGY STUDY. (U)

F/8 9/1

UNCLASSIFIED

JUN 79
PT-5413

N00039-75-C-0451

NL

2
ACB F



END
DATE
FILMED
4 80
DTIC

3.3 Resistivity

Value: Type I and most type IIA $>10^{16}$ ohm cm (20°C)
 Type IIB $10-10^3$ ohm cm (20°C)

Ref. P. Dehham, E.C. Lightowers and P.J. Dean, Phys. Rev. 161, 1967;
P.J. Kemmey and P.T. Wedepohl, Physical Properties of Diamond,
Ed. R. Berman, Clarendon Press, 1965.

NOTE: Diamonds reportedly exhibit considerable photoconductivity
in ultra-violet light when subject to applied electric fields in excess
of 10^6 V/cm. We have not observed any such phenomenon.

References

1. D.R. Decker and A.J. Schorr, "High Power IMPATT Diodes on Diamond Heat Sinks", IEEE Trans. ED, Vol. ED-17, No. 9, Sept. 1970.
2. R. Harper and D. Zavadil, "Traveling-Wave Tube Delay Line Supported on Natural Diamonds", Raytheon Patent Disclosure No. 28540. U.S. Patent No. 3, 778, 665; Dec. 11, 1973.
3. Harper and Zavadil, "2 kW Ku-Band TWT's, Raytheon Report No. MT-547, 24 April 1972. Final Report IDA 523 program.
4. M. Seal, "A Review of Methods of Bonding or Making Electrical Contacts to Diamond", Englehard Technical Bul., Vol. 10, 15, 1969.
5. R. Harper, "Diamond Brazing Method for Slow Wave Energy Propagating Structures", U.S. Patent No. 3, 949, 263; April 6, 1976.
6. Caveney, Jenkins, and Zuidema, "Thermal Conduction Across Metal-Diamond Interfaces", Diamond Research 1971.
7. A.D. Kraus, Cooling Electronic Equipment, Prentice Hall, 1965, pgs. 1-18 and 88-96.
8. W.M. Rohsenow, J.P. Hatnett editors, Handbook of Heat Transfer, McGraw Hill, N.Y., Chapter 3, P.J. Schneider, "Conduction", Table 7.
9. De Vries, "Cubic Boron Nitride: A Handbook of Properties", General Electric Report No. 72CRD178.
10. Slack, "Nonmetallic Crystals with High Thermal Conductivity", J. Phys. Chem. Solids, Vol. 34, pp. 321-335, Feb. 1973.
11. Pope, Horton, and Hall, "Megadiamond, A New Superhard Material", Presented at the Industrial Diamond Association of America, April 10-15, 1972, Scottsdale, Arizona.
12. Hall, "Sintered Diamond: A Synthetic Carbonado", Science Vol. 169, pp. 868-869, August 1970.
13. B.J. Pope, M.D. Horton, H.T. Hall, "High Thermal Conductivity Microwave Substrates", Chemical Engineering Dept, Brigham Young University, Provo, Utah. ECOM-75-1304-F.
14. R. Harper, "Technology Development for Diamond Circuit Supports", Project 75R401, Raytheon Co. Report No. MT-872.
15. R. Harper and U.J. Pittack, "Diamond as a Support Material for TWT Helices", 1976 International Electron Devices Meeting, Dec. 6-8, 1976 Washington, D.C.

References (cont'd)

16. R. Harper and U.J. Pittack, "Diamond as Support Material for Helix TWT's", 1976 Power Tube Specialists Conference, March 16-18, 1976, Monterey, California.
17. Properties of Diamond, De Beers Industrial Diamond Division, London; Published by the Industrial Diamond Information Bureau, Printed by Kenion Press Ltd, Slough, Budes, England.
18. W.M. Rohsenow, H. Choi, Heat, Mass and Momentum Transfer, Prentice Hall, 1961, pgs 104-106.
19. A. Goldsmith, T.E. Waterman, H.J. Hirschorn, Handbook of Thermophysical Properties of Solid Materials Volume I-Elements, Pergamon Press, NY, 1961 page I-187.

Bibliography

1. C.B. Swan, "The Importance of Providing a Good Heat Sink for Avalanching Transit Time Oscillator Diodes", Proc. IEEE (Letters), Vol. 55, March 1967, p. 451-452.
2. R. Berman, Physical Properties of Diamond, Oxford: Clarendon Press, 1965.
3. J. Comeiro, "Properties of Ceramics for Electronic Applications", The Electronic Engineer, April 1967.
4. M. Seal, "The Use of Diamond as a Heat Sink for Solid State Microwave Devices", Proc. International Diamond Conf. Oct. 1969.
5. A.J. Schorr, "A Comprehensive Study of Diamond as a Microwave Device Heat Sink Material", Proc. International Diamond Conf., Oct. 1969.
6. C.B. Swan, et al, "Composite Avalanche Diode Structures for Increased Power Capability", IEEE Trans. ED, Vol. ED-14, No. 9, Sept. 1967.
7. A.T. Collins, E.C. Lightowers and A.W.S. Williams, "Formation of Electrical Contacts on Insulating and Semiconducting Diamonds", Diamond Progress, 1970.
8. F.A. Raal, "The Importance of Bonding to Diamond Surfaces in Industrial Application", paper presented at the 1968 Diamond Conference, Univ. of Bristol, England.
9. R. Berman, "Diamond Heat Sinks", Electronic Engineering, August 1970, p. 43, 45.
10. R. Harper, "Wire Wrapped Diamond Supported Helix Assembly", Raytheon Patent Disclosure No. 31088; Feb. 16, 1976.
11. H. Schmidt Brucker and W. Schlapp, "Festhaftende Diamant/Metal-Verbindung", Zeitschrift Fur Angewandte Physik, Vol 32, No. 4, p. 307-310, 1971.
12. M. Neuberger, "Diamond", Hughes Aircraft Co., Data Sheet DS-153, March 1967 Air Force Materials Laboratory Contract AF33(615)-2460 (AD-812827).
13. Amzirc - Technical Data, American Metal Climax, Inc., New York, 1968.
14. Karkliva and Maslakovets, "Concerning Etching of Diamond", Soviet Physics-Doklady, Vol. 13, No. 12, June 1969, pp. 1194-1195.
15. Spencer and Schmidt, "Ion Machining of Diamond", JAP, Vol. 43, No. 7, July 1972, pp. 2956-2958.